THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

CHALMERS

Demystifying the effectiveness in design of production systems

Investigating the coupling between acquisition and maintenance of equipment

MALIN HANE HAGSTRÖM

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Göteborg
Telephone +46 (0)31-772 1000

Demystifying the effectiveness in design of production systems
Investigating the coupling between acquisition and maintenance of equipment

MALIN HANE HAGSTRÖM

Technical report no IMS-2021-23

Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Reproservice
Gothenburg, Sweden 2021

Abstract

The purpose of the design of production systems is to create systems that perform according to set targets. With the paradigm shift towards electrification and digitalisation, manufacturing engineers in the heavy truck powertrain industry face several unexplored challenges; in the products for which they are designing production, in the equipment they are purchasing to realise production systems, and finally, in the digitalisation impact on engineering processes. Further, there is a lack of empirical studies on the performance of production system design, measured as the performance of production systems when they are in operation. Understanding performance of design is vital in order to identify and implement correct improvement measures.

To investigate the performance of production system design, this thesis presents comparative case studies from powertrain manufacturing engineering in a large heavy truck company. The focus is on the equipment acquisition process and its impact on the performance of the purchased equipment and specifically equipment breakdown cost due to design weakness. The investigation was performed both quantitatively, comparing breakdown costs for newly acquired equipment to equipment nearing their end of life, and qualitatively, comparing the ability to prevent breakdowns in four re-purchasing acquisition projects. The thesis shows that: 1) maintenance cost per machine is increasing during the initial phase of the life cycle; 2) new machinery have higher breakdown costs than the end-of-life machines; 3) the design weakness share of maintenance problems unexpectedly only increases during the initial phase of the life cycle. The conclusion is that the engineering process studied does not become more effective over time.

The main barriers to effective design of production systems are found to be connected to how knowledge flows internally and externally in the organisation, and more specifically during the organisational and individual dimensions, rather than the technological aspect. Further research in knowledge management is recommended as well as a study of how digitalisation might benefit the production system design engineering community from a socio-technological point of view.

Keywords: production system design, manufacturing engineering, equipment acquisition, early equipment management, engineering knowledge management, maintenance management

Acknowledgements

I would recommend everyone to start an academic journey in the middle of an industrial career. Being part of the Department of Industrial and Materials Science has truly opened my thinking and has given me access to so many interesting fields that I could never have imagined when starting this journey. In my mind, bringing together the two worlds of academy and industry has had benefits for both areas. For industry I have been able to connect our organisation more directly to state-of-the-art research, whereas for academy I have provided an arena within academics can perform trailblazing research. Both Chalmers University of Technology and Powertrain Production of Volvo Group Truck Operations have demonstrated faith in my abilities while I have been pursuing both my professional and academic ambitions for which I am very grateful.

At Chalmers I would like to express my deepest gratitude to Professor Dag Bergsjö, my supervisor, to my co-supervisor Professor Ola Isaksson and to the Chalmers Production Area of Advance. At Powertrain Production I want to express my deepest gratitude to Sr Vice President Anders Olausson and Vice President of Quality, Environment and Volvo Production System, Jan Berg. I am very grateful for the support, insights and encouragement that Lena Moestam, Sr RnD Engineer has provided me as my industrial supervisor. All of you have been instrumental in helping me realise my professional goals.

My gratitude also extends to the Swedish Governmental Agency for Innovation, VINNOVA, and specifically the research projects MALEKC, studying machine learning for knowledge intense processes, and KIDSAM, investigating knowledge intense cooperation. I also want to acknowledge Certified Translator Gunilla Ramell for her excellent editing and support.

Finally, I have had the pleasure of connecting with so many knowledgeable individuals and have found new friends for which I am grateful for.

Malin Hane Hagström

Gothenburg, Sweden, 2021

Appended Publications

The following publications are included in this thesis:

Paper A

Hane Hagström, M., Bergsjö, D., Sathyanarayana, A., Machado, C. (in review). Visualising wastes and losses in automotive production flows (across multiple plants and organisations) for increased accuracy in improvement prioritisations

In review in international journal

Distribution of work: Sathyanarayana, A. and Machado, C. performed the data collection under supervision of M. Hane Hagström. The planning, analysis and writing of the paper was conducted by M. Hane Hagström. D. Bergsjö contributed with ideas and as reviewer.

Paper B

Hagström, M. H., Gandhi, K., Bergsjö, D., & Skoogh, A. (2020). Evaluating the effectiveness of machine acquisitions and design by the impact on maintenance cost–a case study. IFAC-PapersOnLine, 53(3), 25-30.

Distribution of work: Gandhi, K. performed the data collection and initial analysis. The concluding analysis was performed M. Hane Hagström and K. Gandhi. The planning, analysis and writing of the paper was conducted by M. Hane Hagström and K. Gandhi. D. Bergsjö and A. Skoogh contributed with ideas and as reviewer.

Paper C

Hane Hagström, M., Bergsjö, D., Martinsson, H., Blomberg, J., (in review). Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions

In review in international journal

Distribution of work: Martinsson, H. and Blomberg, J. performed the interviews under supervision of M. Hane Hagström. The planning, analysis and writing of the paper was conducted by M. Hane Hagström. D. Bergsjö contributed with ideas and as reviewer.

Other Publications

Eckert, C., Isaksson, O., Eckert, C., Coeckelbergh, M., & Hagström, M. H. (2020). Data Fairy in Engineering Land: The Magic of Data Analysis as a Sociotechnical Process in Engineering Companies. Journal of Mechanical Design, 142(12).

+

Table of Figures

Table of Tables

1. Introduction

Efficient production systems are necessary for the realisation of products that fulfil customer needs and delivery requirements (Bellgran, 2003). Bellgran continues; "Designing a production system is a unique and complex task in which many parameters should be taken into account during the process of creating, evaluating and selecting the proper alternative". The importance of design, in particular as an industrial activity and the increasingly complex and dynamic context in which it takes place, has led to the desire to improve the effectiveness and efficiency of design practice (Blessing & Chakrabati, 2009). This also applies to the design of production systems.

To investigate the effectiveness and efficiency of production system design, this thesis presents comparative case studies from powertrain manufacturing engineering in a large heavy truck company. The focus is on the equipment acquisition process and its impact on the performance of the purchased equipment in terms of breakdown cost due to design weakness. The investigation was performed both quantitatively, comparing breakdown costs for newly acquired equipment to equipment nearing the end-of-life, and qualitatively, comparing the ability to prevent breakdowns in four re-purchasing acquisition projects.

For this thesis, the concept of "end-product" represents the finished goods that are sold to customers. The concept of "product" refers to equipment, in this case to a large extent subtractive manufacturing machines that are acquired, sometimes using the synonym purchased, and installed to manufacture the end-product. The terms "effectiveness" and "efficiency" are used based on the Merriam-Webster dictionary where effectiveness is defined as the capability to produce a desired effect (effectiveness, 2021), whereas efficiency is defined as the capability to produce something with little or no waste (efficiency, 2021). An effective and efficient *production system* is producing the agreed-on and desired end-products according to the correct specifications with little or no waste. With a similar analogy, an effective and efficient *production system design* is a design process that delivers an agreed-on and desired production system and is performing the design process with little or no waste.

1.1. Background

Organisations often define functional areas around the end-product starting with requirements analysis and planning, concept engineering and prototyping, product engineering, manufacturing engineering, manufacturing and production, sales and distribution and, finally, disposal and recycling as illustrated in Figure 1 below.

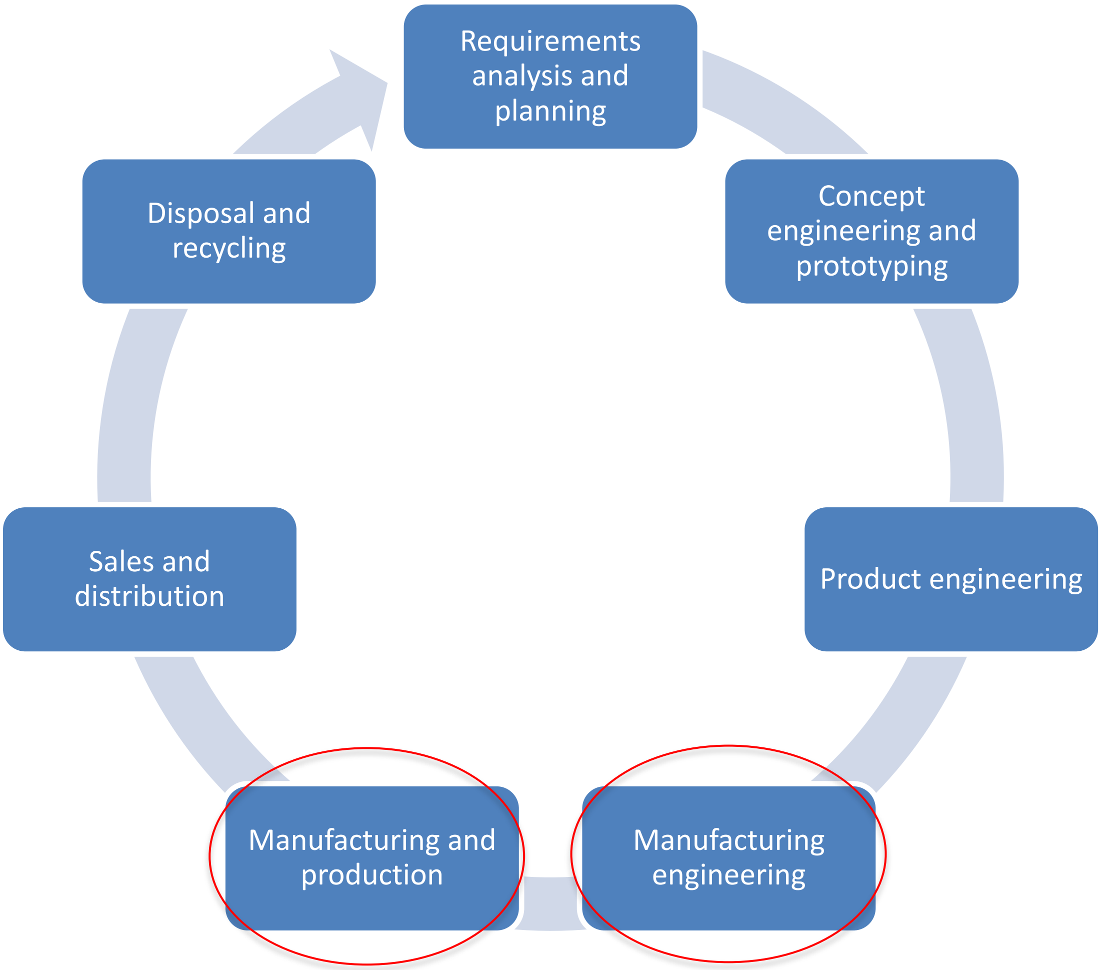


Figure 1: Illustration of functional areas that comprise a product's life-cycle with the focus of this thesis circled. Inspired by (Grieves, 2006).

The purpose of manufacturing engineering is to design a production system that performs according to set targets. Since the performance of the manufacturing and production system is significantly influenced by the design of the system (Pistikopoulos et al., 2000), it is valid to study the knowledge feedback between the performance of the existing production system and the design of that system. A large part of the daily job in production is to solve problems. These problems have a tendency to repeat themselves, meaning that production repeatedly has to solve the same problems (Bokrantz et al., 2017). Traditionally, it has been difficult for organisations to collaborate across organisational barriers, maintain an holistic view of the entire performance of the company, and avoid the risk the functional areas become isolated silos with little communication or coordination among them (Grieves, 2006).

A major task of manufacturing engineering is to purchase the required equipment, referred in Figure 2 to the *equipment acquisition phase* for the production system, to function as desired. The equipment type for this thesis is of a capital-intensive nature, which means that the design, purchase, and maintenance of equipment needs to be carefully managed.

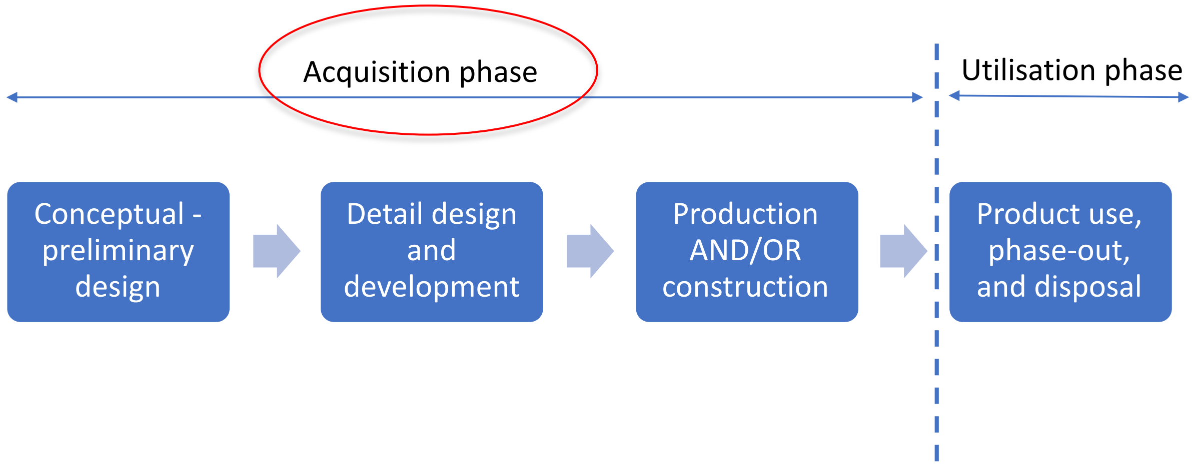


Figure 2: The product life-cycle from the perspective of a system engineering process, highlighting the difference between the acquisition phase and the utilisation phase. Inspired by Blanchard and Fabrycky (1998)

1.2. Research focus

The aim of this study is to acquire an understanding of how effective and efficient the production system design process is, with a focus on equipment acquisition and the performance of the acquired equipment in terms of breakdown cost in production in order to prioritise improvement needs in the production system design process. Figure 3 visualises the relevant identified areas to describe the research gap and research focus for this thesis.

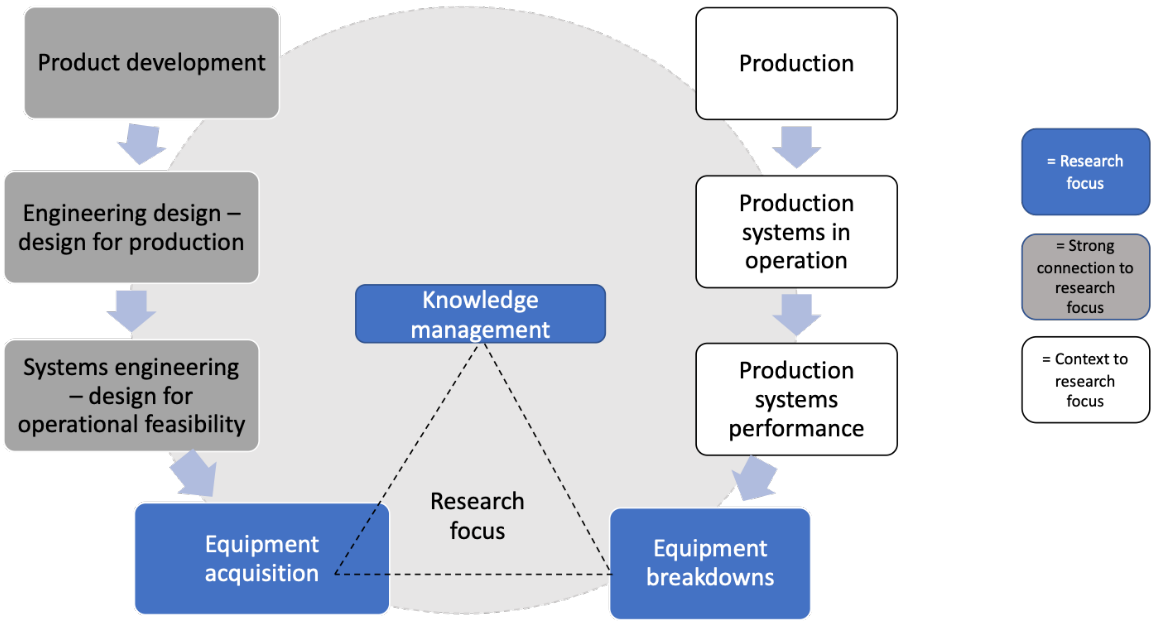


Figure 3: Identified relevant areas to describe the research gap and research focus of this thesis

1.2.1. Industrial problem

There are many driving forces currently taking place that radically impact industry. These forces include the strong drive to go from fossil-fuelled to electrified products, the impact that digitalisation will have on production systems, as well as the impact of digitalisation on traditional ways of working in engineering. The acquisition process and manufacturing engineering community will accordingly be impacted with several unexplored challenges:

a) The electrification of end-products for which production is designed
b) The Industry 4.0 (Schwab, 2017) implications on the equipment purchased to realise the production system
c) The digitalisation impact on the engineering processes in themselves

These challenges will be further described below.

a) The challenge of electrification of today's fossil-powered powertrain end-products:

Regarding the *new end-products*, Denger and Zamazal (2020) state that "new features and functionalities, as well as the increasing share of electronic components and software in products, increase system complexity, not to mention automotive trends, such as electrification, autonomous driving and connected and frequently updated vehicles", constitute major challenges facing modern manufacturers. With the rapid transformation from fossil-fuel to electric drivelines, the powertrain industry in the truck market segment needs to develop business models, solutions and products that are completely new and unexplored. External market reports show that the global electric truck market is forecast to reach 1,500,000 units by 2025, from less than 100,000 in 2013 (P&S Intelligence, 2018). The combustion engine is more than 100 years old and has served as a heritage and knowledge base for the entire powertrain engineering community for both product development and the corresponding production system to produce these products. The production system that should now produce the electric drivelines possesses completely different characteristics which is why new knowledge needs to be created for the engineering community. The dominant production processes for combustion engines have traditionally been casting metal, high precision machining of the metal and then to a large extent manually assembling external parts onto the machined metal. With electrification, the battery becomes the central part where the main challenges today are to reduce the size and cost of the battery. Other top challenges mentioned by Denger and Zamazal are time-to-market goals, low innovation rates together with an increase in product quality and product life-cycle cost control. All these challenges will have significant impact on the manufacturing engineering processes.

b) The challenge of Industry 4.0 implications on production equipment:

Regarding the *equipment*, Industry 4.0 is transforming manufacturing systems. A market report from Fortune Business Insights in 2021 projects that the European Industry 4.0 market will grow from \$116.14 billion in 2021 to \$337.10 billion in 2028 at a compound annual growth rate of 16.4% during the period 2021-2028, and that the Covid pandemic has been accelerating this growth (Insight, 2021). Industry 4.0 is described as the fourth industrial revolution, the first being the invention of the steam engine, the second the invention of electrical engines and the third computers and the internet. The fourth industrial revolution with automation and computers aggregating into "the internet of things" (IoT) and big data analysis, towards enabling the usage of IoT and collaborative and proactive solutions (Bokrantz et al., 2017). When in place, the Industry 4.0 factory should have developed into an intelligent environment in which the system of production equipment is exchanging information, triggering actions and controlling each other autonomously (Weyer et al., 2015). It is evident that machines will be performing more complex tasks and require higher availability which will place high demands on designing the production system, on acquiring the machines and enabling the ability to maintain them. This will presumably lead to an increased amount of factory automation, together with information about everything from quality of end-products to which type of maintenance might be needed for the production equipment (Li et al., 2019), to name a few examples. Another paradigm shift is the transfer to circular economy. Circular economy is considered to be an innovative approach used to increase resource efficiency in companies by keeping equipment functioning for as long as possible (Wakiru et al., 2018). This implies that society needs to increasingly improve its ability to design for sustainability which means designing for maintainability.

c) The challenge of digitalising the engineering process:
Finally, the digitalisation impact on the *engineering process itself* could be vast. Society is demanding shorter development cycles and increased resource efficiency (Lasi et al., 2014)."Interlinked and autonomous manufacturing systems provide new opportunities in smart manufacturing. Today's manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity (Stark et al., 2017). Stark et al continue, "In reality, the manufacturing system design barely even follow a systematic design approach: it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (…) without any true systems engineering design opportunity". Lasi et al. (2014) state that "The term "Industry 4.0" describes different – primarily IT driven – changes in manufacturing systems. These developments do not only have technological but also versatile organizational implications. As a result, a change from product- to service-orientation is expected even in traditional industries."

1.2.2. Research gap

For any manufacturing actor in a highly competitive global market, the production system is essential for the prosperity or even survival of a company. The importance of production system capabilities is increasingly acknowledged. However, the process of designing the production system has received little attention, ignoring its potential for gaining a competitive edge (Bellgran & Säfsten, 2009; Bruch, 2012). Bruch states: "Designing production systems in an effective and efficient manner is advantageous as it supports the possibility of achieving the best possible production system in a shorter time". Islam et al state that there is still a lack of empirical studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap (Islam et al., 2020).

The research gap can be summarised as a lack of empirical studies on the effectiveness and efficiency of the production system design process.

1.3. Research motivation and questions

In this thesis, the research gap is addressed by performing a pre-study to establish an arena by which the research gap can be investigated (Paper A). The pre-study showed:

1. Machine breakdown is one of the most expensive disturbance types in the production system in the supply chain studied
2. The production equipment acquisition process is the production system design process that mostly influences machine breakdown

From that result, the following research questions have been formulated to guide the study:

RQ1: What is the current capability of a manufacturing firm to address equipment breakdown issues already during the production equipment acquisition phase?

The capability to design production systems that minimise the breakdown cost deserve further study. As the costs of breakdown of equipment are significant for manufacturing companies, the first research question sets out to identify and analyse the current capability in a case company to acquire equipment that minimises the disturbance in the production system by the cost of the broken-down equipment.

RQ2: What are the barriers that prevent us from capturing, sharing and re-using equipment breakdown knowledge from production into the production equipment acquisition phase?

As all design work is highly dependent on knowledge, the second research question sets out to identify any barriers for knowledge about the current performance of the production system in terms of cost of equipment breakdown to be captured, shared, and re-used in the production system design process and more specifically to the equipment acquisition process.

1.4. Delimitations

This thesis focuses on describing one of the main problems identified, equipment breakdown, is investigating quantitative data from equipment in one specific plant and is also studying four acquisition projects, all in the same company. The following areas are excluded from the scope of the thesis:

Analysis of all value flows in the company

As it is difficult to study all value flows in terms of time and resources, one significant flow of end-product was selected

Deep analysis of all types of production disturbances

As it is difficult to study all types of production disturbances in terms of time and resources, a pre-study was performed to identify the most significant disturbances

Prescribing any specific solutions

As this thesis is a descriptive thesis, no prescriptions or tests are performed. This thesis is solely describing the phenomena as of today

2. Frame of reference

In this chapter, the underlying theories and accompanying subjects that will support the research are presented.

Research is performed within and reflected towards certain frameworks of knowledge that previous researchers have gained, developed and cultivated. These frameworks of knowledge consist of relevant methods, results from studies and how these results may be interpreted for various contexts. These frameworks also function to frame the research, position the results and define where the research gaps are which is important to be able to define the research contribution.

The overarching framework for this thesis is in the field of product development. The "product" of this thesis is the production system; the focus is on development of production systems. Within the research framework of product development, the main interests reside in systems engineering and engineering design. Within systems engineering, the focus is on design for operational feasibility and, specifically, design for reliability. Within engineering design, the focus is on design for production. Figure 4 visualises the relevant fields of interest.

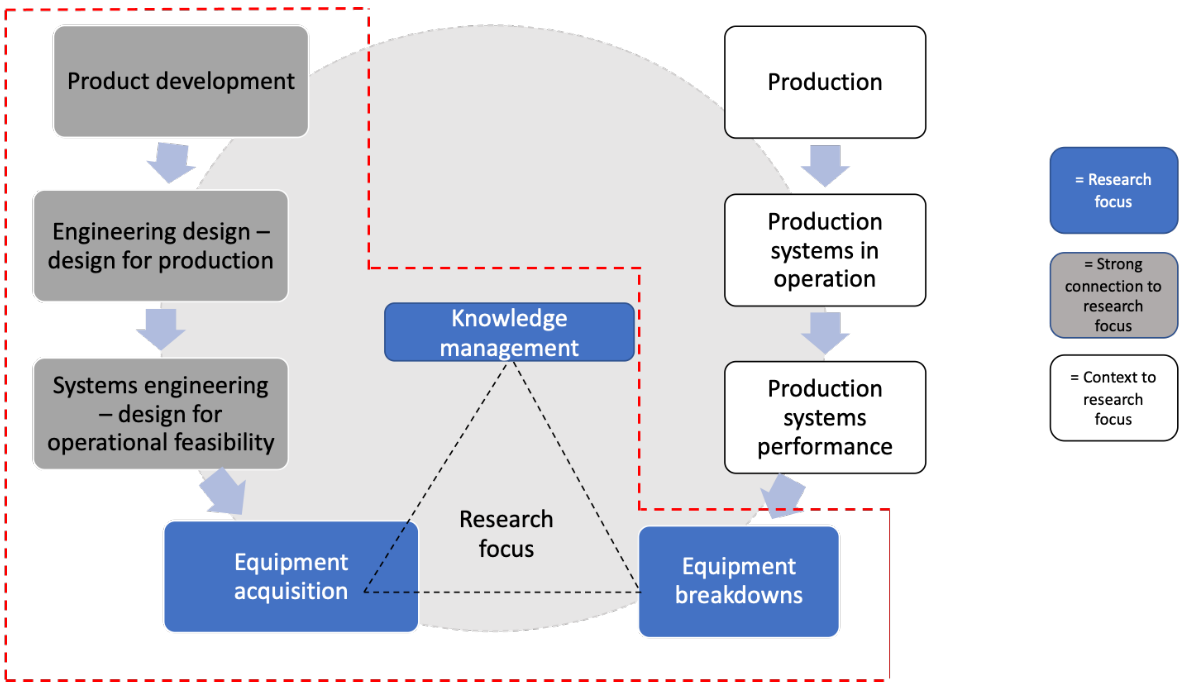
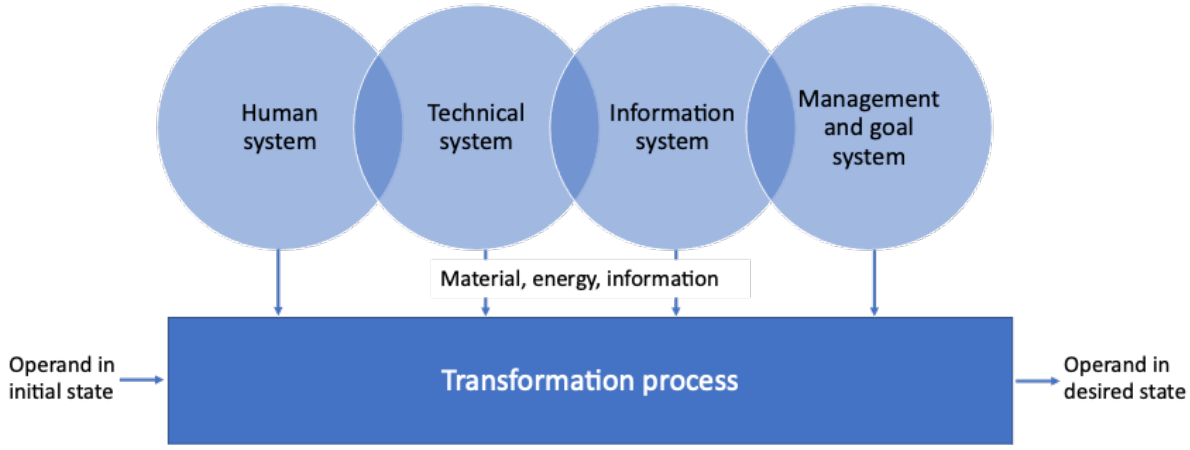


Figure 4: Identified relevant areas to describe the research gap and where the research focus for this thesis lies

2.1. Production systems performance

To give context to the research focus, the "product" studied in this thesis is the production system. Production is the transformation process whereby an input into a system is transformed into an output (Wu, 1994). It is a process of combining materials, resources, labour and capital in order to create products and/or services (Jonsson & Mattsson, 2009). A number of areas are required for the transformation: technology, people, energy and information need to be organised and managed in an effective way to make the transformation possible (Bellgran & Säfsten, 2005). The production system requires an holistic perspective and the sub-parts of the system with their internal relations contribute to realising the transformation. Facilities, people, and equipment (e.g., machines), software and procedures are considered to be elements of the production system which all have relations to each other (Löfgren, 1983). Figure 5 presents a simplified illustration of a transformation system, such as a production system.



For the performance of a production system, the lean approach has been the dominant model to

Figure 5: A simplified mode of a production system from Hubka and Eder (1988)

define relevant metrics and approaches to improve performance. According to Womack et al. (1990), one of the major goals of lean manufacturing is to implement a philosophy of continuous improvement that allows companies to reduce costs, improve processes and eliminate waste to increase customer satisfaction and profit. Lean manufacturing provides companies with the tools to survive in a global market that demands higher quality, faster delivery and lower prices, at volumes required to sustain the business. Specifically, its main objectives are to: (a) drastically reduce waste in the supply chain, (b) reduce inventory and space occupied on the production floor, (c) create more robust production systems, (d) create appropriate systems for the delivery of materials and (e) improve the organization's production areas in order to increase flexibility, a factor that is growing increasingly important considering the rapid changes in customer demands (Alves & Alves, 2015).

2.2. Product development

This thesis refers to the product development phases as presented by Ulrich et al. (2020), shown in Figure 6. In this framework, development is defined as “the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product”, whereas design is defined as “defining the physical form of the product to best meet customer needs, including engineering design (mechanical, electrical, and software)”. Pahl and Beitz (1996) use the term design synonymously for design and development.

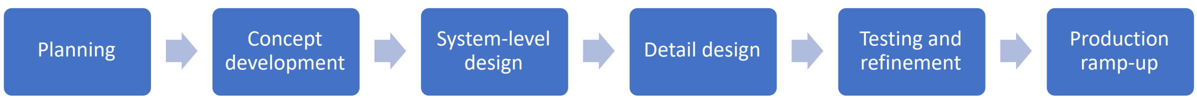


Figure 6: Phases of the product development process, after Ulrich et al. (2020)

Ulrich et al describe each phase in a generic level:

1. *Planning:*
   This phase precedes the project approval and launch of the actual product development process and begins with opportunity identification guided by corporate strategy and includes assessment of technology developments and market objectives.
2. *Concept development:*
   In this phase, the needs of target markets are identified, alternative product concepts are generated and evaluated, and one or more concepts are selected for further development and testing.
3. *System-level design:*
   This phase includes the definition of product architecture, decomposition of the product into subsystems and components, preliminary design of key components and allocation of detail design responsibility to both internal and external resources.
4. *Detail design:*
   This phase includes the complete specification of the geometry, materials and tolerances of all of the unique part in a product and the identification of all standard parts to be purchased from suppliers.
5. *Testing and refinement:*
   This phase involves the construction and evaluation of multiple preproduction versions of the product.
6. *Production ramp-up:*
   In this phase, the product is made by using the intended production system. The purpose is to train workforce and work out any remaining problems in the production processes.

The development of a production system follows these steps as well, and this thesis focuses on the capabilities to follow the steps in design for production with the aim of designing for reliability. When applying the model above and focusing on production design and development of the production equipment, Figure 7 describes the critical deliverables per each phase:

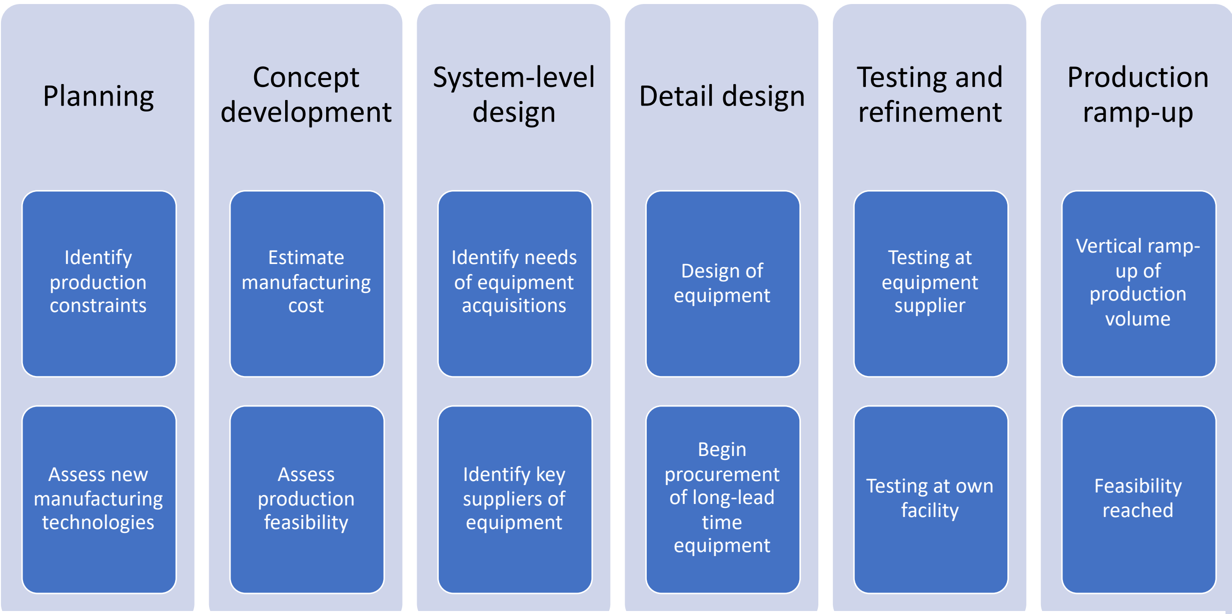


Figure 7: Critical deliveries in the product development phase regarding design and development of the production system equipment

Ulrich et al. (2020) state that one major challenge of the product development process is to transfer a tremendous amount of information and knowledge within and between development teams. Other challenges in traditional product development models usually lead to a number of problems commonly seen in companies, some of which are: (i) work overload of designers and engineers that frequently perform unnecessary tasks, (ii) models that are not clearly understood by designers, (iii) project cost overruns, (iv) difficulty in retrieving knowledge from previous projects and (v) ambiguity regarding tasks' responsibilities due to insufficient commitment of functional departments (Tortorella et al., 2016). When applying the lean philosophy in design, the main principles are the same but the application differs. There have been many efforts to define Lean Product Development more precisely (Tortorella et al., 2016) and several definitions exist. Ward (2007) defined Lean Product Development "as a set of operational value streams that should be designed to consistently execute product development activities effectively and efficiently, creating usable knowledge through learning. The building blocks of such value streams and knowledge creation cycles are organised along five principles: value focus, entrepreneurial system designer, teams of responsible experts, set-based concurrent engineering and cadence (pull and flow)." The term "usable knowledge" is defined as the value adding part of lean product development, i.e. for the design of the production system, it is critical to focus on the knowledge creation in the design process to enable the production system to support the lean principles of production.

2.3. Engineering design - design for production

Engineering design research has been defined as "the study of principles, practices and procedures of design" (Cross, 1984). The main task of engineers is to apply their scientific and engineering knowledge to the solution of technical problems and then optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations (Pahl & Beitz, 1996). Figure 8 describes the central activity of engineering design from Penny (1970).

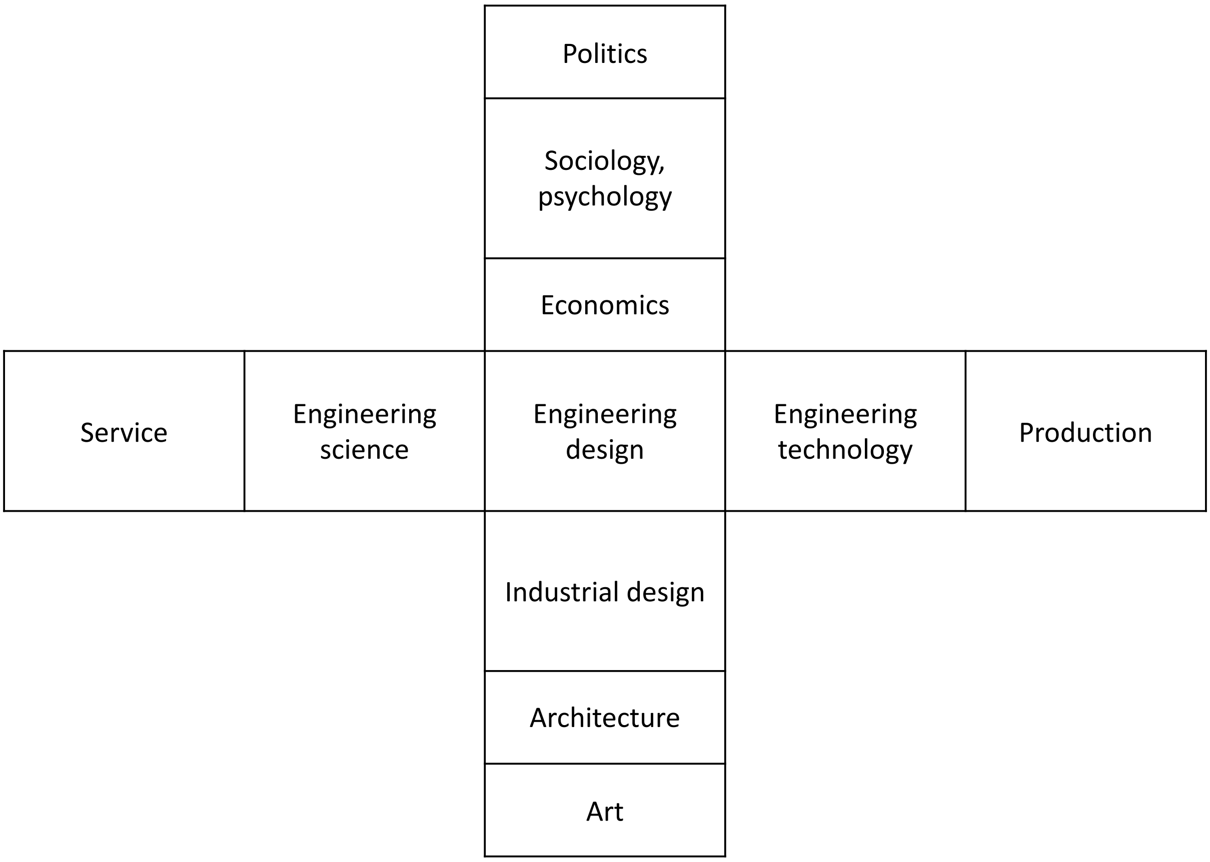


Figure 8: The central activity of engineering design. from Penny (1970).

Whereas engineering design is traditionally seen from a physical product perspective, Pahl and Beitz (1996), continue that "design tasks related to production machines, jigs and fixtures and inspections equipment (…) fulfilling the functional requirements and technological constraints are equally important". They also mention that it is important that there be a systematic methodology in place to ensure designers reach potential solutions quickly and directly, and that it is important for design methodology to foster and guide the abilities of designers, encourage creativity and at the same time focus on the need to objective evaluations of results. Systematic design aims to rationalise the design and production processes.

Pahl and Beitz (1996) also discuss design for production, the purpose of which is to design the product in a way that minimises production costs and times while maintaining the required quality of the product. The importance of equipment performance is stated as a potential cause changes to performance, failures and dangerous situations which can substantially reduce the functionality, economy and safety. Sudden breakdowns disrupt normal operations and because they are unexpected involve considerable cost to rectify. Design for ease of maintenance is mentioned as a concept in itself. From an engineering design perspective, maintenance requirements should be included in the requirements list and stated examples are variants that require minimal servicing, easily exchanged components and use of components with similar life expectancies. A technical solution should in principle require as few preventive measures as possible. The aim is complete freedom of service by using components of identical life, reliability and safety.

2.4. Systems engineering – design for operational feasibility: reliability

Systems engineering is focused on the process of bringing human-made systems into being, beginning with the definition of need and extending through requirements analysis, functional analysis and allocation, design synthesis, design evaluation and system validation (Blanchard & Fabrycky, 1998). Systems engineering focuses to ensure that human-made systems are properly coordinated and functioning with a minimum of undesirable side effects, such as costly and disruptive consequences. A system is a combination of elements or parts forming a uniform whole, and a system is composed of components, attributes and relationships between integrated parts.

Within systems engineering, design for reliability is one aspect. Reliability may be defined as the probability that a system or product will perform in a satisfactory manner for a given period when used under specified operating conditions. Blanchard and Fabrycky (1998) continue: "Reliability is one of the most important design parameters. Many systems today are highly sophisticated and will fulfil most expectations when operating. However, experience has indicated that these systems are inoperative much of the time, requiring extensive maintenance and expenditure of scarce support resources. In an environment of scarce resources, it is essential that reliability be considered a major system parameter during the design process". Sherwin (2000) states that maintenance management has always been one step behind the development of production systems. Figure 9 describes how the reliability aspects are valid throughout the life-cycle of a product, and, in the case of this thesis, in the design of a production system.

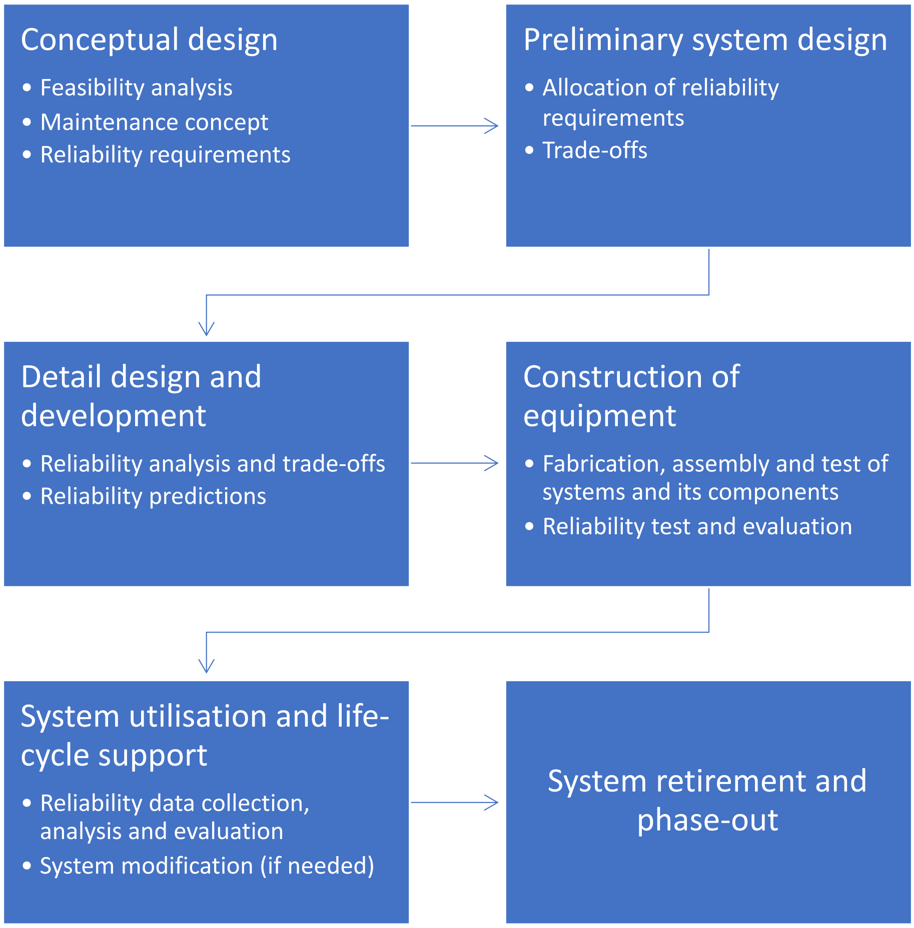


Figure 9: Reliability requirements in the production system life-cycle. Inspired from Blanchard and Fabrycky (1998)

2.5. Equipment acquisition

Ulrich et al. (2020) define the manufacturing and supply-chain system input-output model in Figure 10. The equipment input is one of several fundamental inputs to the manufacturing system.

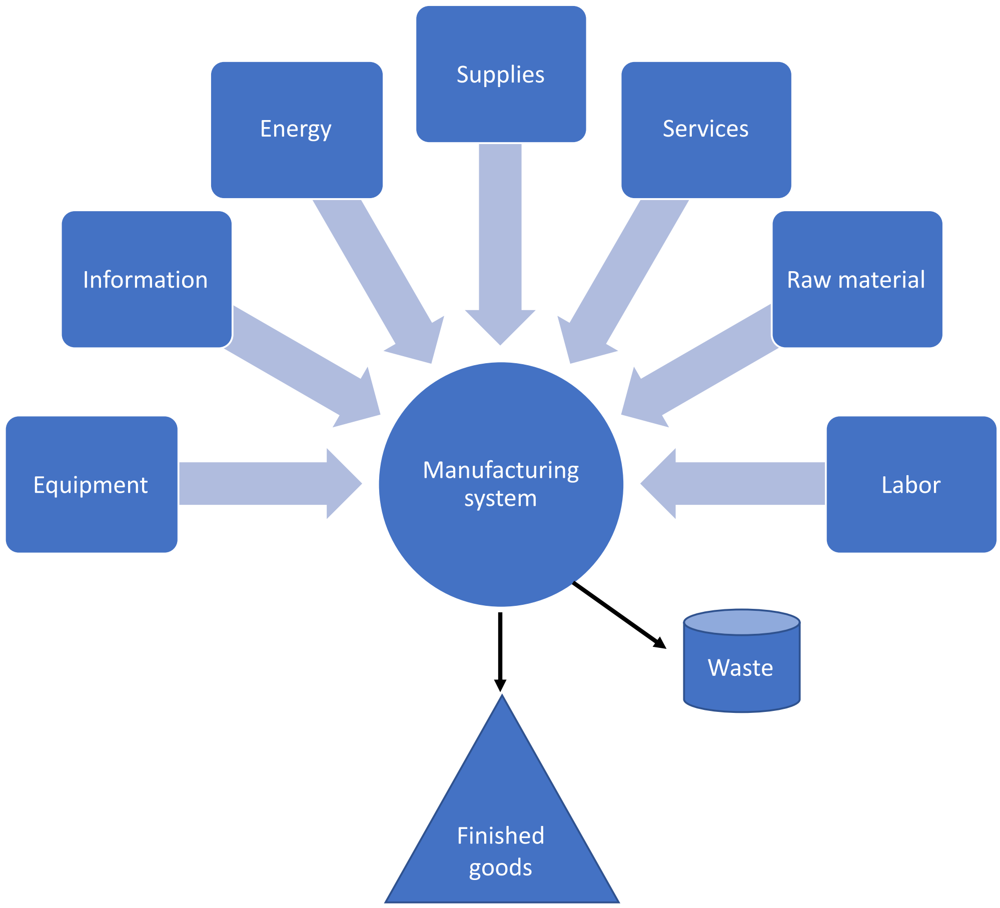


Figure 10: Manufacturing and supply-chain system input-output model, inspired by Ulrich et al. (2020)

Blanchard and Fabrycky (1998) also mention the equipment acquisition as an important activity and separate the acquisition phase and utilization phase to recognize producer and customer activities as is shown in Figure 11. They further state that it could be limiting to only look at the product when talking about product development, but that the manufacturing process, utilization, maintenance, and disposal processes must also be considered.

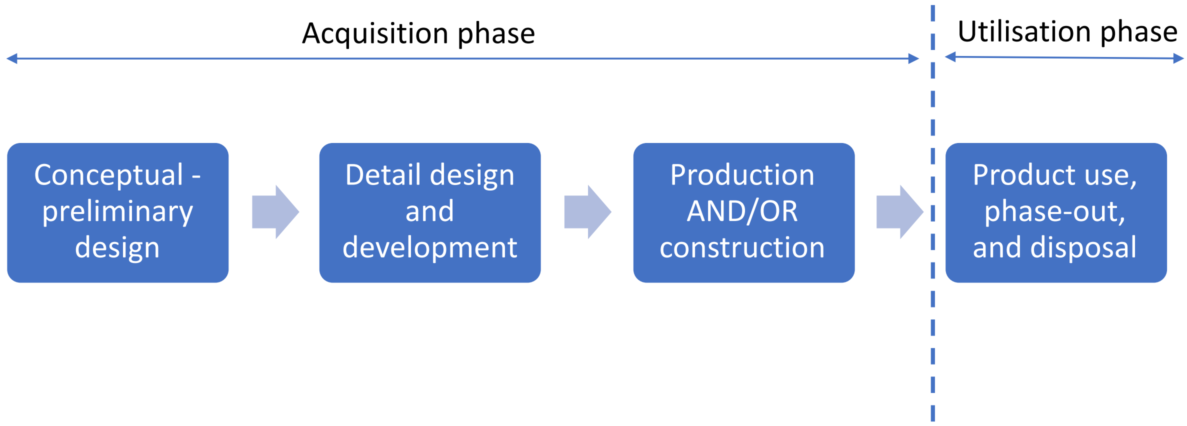


Figure 11: The product life-cycle from a system engineering process, highlighting the difference between the acquisition phase and the utilisation phase. Inspired by Blanchard and Fabrycky (1998)

The equipment acquisition process is defined as "This innovation activity refers to goods specifically purchased for use in the product and process innovation activities of a firm. This includes the acquisition of land and buildings (including major improvements, modifications and repairs); machinery, instruments and equipment (including computer hardware) as well as computer software. This category only includes the acquisition of capital goods for innovation that is not included in R&D activities" (OECD, 2005).

There are various reasons why a company would like to invest in new machinery, including increasing capacity, introducing new products or phasing-out of obsolete spare-parts. In this definition equipment acquisition concerns machines that are not bought off the shelf but rather designed to order, leading to longer lead times and higher procurement cost (Yeo & Ning, 2006). To meet this challenge a well-developed collaboration between supplier and buyer is advocated (Hoegl & Wagner, 2005). Equipment investments are usually conducted in projects, which entails project metrics, such as time and cost (Jha & Iyer, 2007). However, at issue is not only the investment but also procuring the best possible equipment for production and maintenance by using existing knowledge and experience. To be more resource efficient, front-loading information gathering and knowledge transfer in a project is preferred. The later a problem arises in a project, the more expensive they are to handle, as the cost of design changes rapidly increase when incurred late in the development process (Folkestad & Johnson, 2001).

To make sure that adequate knowledge is available for ongoing projects, several activities need to take place outside of the project environment (Stenholm, 2018). Knowledge should be collected from several parts of the organisation and be fed into the procurement process to ensure the best equipment is purchased from several operational angles. Maintenance has been found to be a major contributor to achieve equipment stability and is one of the success factors in equipment acquisition (Gulati, 2013). Several production disturbances are often experienced after installing new machinery, such as difficulties in maintainability, complex equipment, safety issues and difficulties in achieving high efficiency from start of production. It is by identifying the root cause of these potential future disturbances already during the development phase that they can be eliminated (Axelsson, 2005; Bellgran & Säfsten, 2009; Gulati, 2013) .

2.6. Equipment breakdowns

Equipment breakdowns are normally described in the field of maintenance. The Swedish Standards Institute describes maintenance as “the combination of technical and administrative actions, including monitoring, intended to maintain or restore a device to such a state that it can perform the required function” (SIS, 2000). Further on, Gulati (2013) describe maintenance as the work of keeping the condition of the production equipment in such a way that it can achieve its intended production efficiency (Gulati, 2013). Events that disturb the intended production condition can be regarded as disturbances or losses of production. The activities in maintenance are both activities that prevent failures of the equipment but also activities that restore equipment into original condition. All maintenance activities have a target of maximizing production capacity and reducing overall costs of production (Bellgran & Säfsten, 2009).

The maintenance cost increases nearly exponentially closer to the end of the equipment life-cycle and it is in the design stage that it is possible to prevent many of the causes of production disturbance in a cost-efficient way (Bellgran & Säfsten, 2009; Gulati, 2013). Despite the potential cost savings, studies show that awareness of the cost incurred with breakdowns and maintenance losses is low among respondents in Swedish industry (Salonen & Tabikh, 2016). Other studies show that even though the importance of maintenance have been acknowledged, industry underperforms due to underinvestments in maintenance organisations (Lundgren, 2019).

Lundgren further mentions that it is important to link the maintenance cost and potential production disturbances already in the procurement process. This is also supported by Salonen (2018) who showed that 65% of recorded data from eight automotive sites in Sweden registered design weaknesses of the machine as the root cause of breakdowns. In addition, 23% of the breakdowns were related to poor professional maintenance performed. The article also mentions that a missing area of research is how to manage the procurement and/or design of dependable production equipment, which further highlights the research gap covered by this thesis.

2.7. Knowledge management

Design and development are highly knowledge-intensive activities (Blessing & Chakrabati, 2009). To better understand the concepts on how to improve knowledge sharing, some basic concepts around knowledge management are needed. A distinction usually made is between data, information and knowledge at different levels of abstraction. Data are raw numbers and text that can exist in a database of some sort, information is data processed and put into context and knowledge is this information processed by a researcher and put into a relationship (Dretske, 1981; Vance, 1997).

A tool used to both evaluate and help reason about knowledge in organisations is the Knowledge Value Chain (KVC) (Lee, 2016). KVC is adopted from the business value chain model by Porter (1985) which is describing how value is created and contributing to corporate competitive advantage. KVC, as discussed by Lee and Yang (2000), describes the process of knowledge management in five activities:

1. Knowledge Acquisition – Finding information which can be conducted by either actively searching for it through a knowledge management infrastructure or through creating a ”learning organisation”, as proposed by Senge (1990) with the first one usually connected to explicit knowledge and the latter to tacit knowledge.

2. Knowledge Innovation – Creating knowledge by individuals through four different modes of knowledge conversion (Nonaka & Takeuchi, 1995)
    a. from tacit knowledge to tacit knowledge, i.e. socialisation
    b. from tacit knowledge to explicit knowledge, i.e. externalisation
    c. from explicit knowledge to explicit knowledge, i.e. combining.
    d. from explicit knowledge to tacit knowledge, i.e internalisation.

3. Knowledge Protection – Protecting the knowledge concerning Intellectual Property Rights (IPR), such as patents and copyrights. In addition, cybersecurity and access rights falls under this segment.

4. Knowledge Integration – Contextualising the knowledge to make it understandable and relevant to the organisation.

5. Knowledge Dissemination – Making the knowledge available for the organisation, to a large extent a social process even though IT systems are considered useful for explicit knowledge.

These activities are supported by four components of the knowledge management infrastructure which can be seen in the visual KVC representation in Figure 12 below.

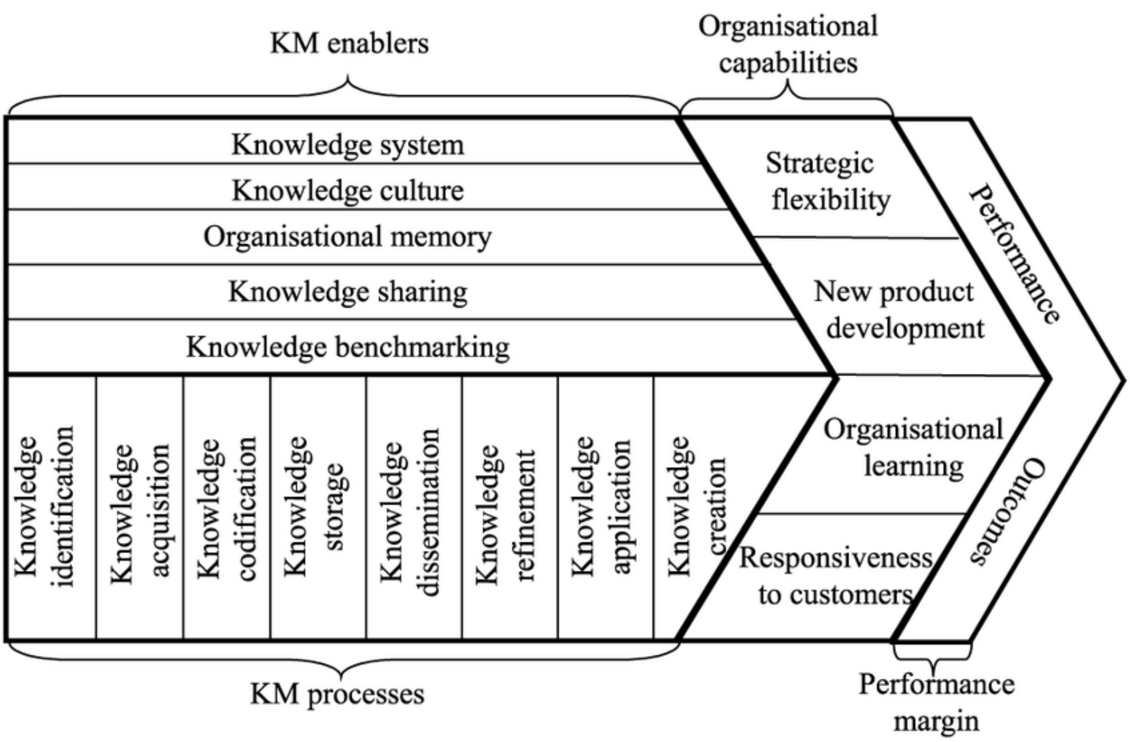


Figure 12: A visual representation of the Knowledge Value Chain. Adapted from Lee and Yang (2000)

A supportive knowledge management infrastructure together with a well-working process is what creates knowledge value for businesses, which is important for their competitiveness in today's market (Lee, 2016).

Wynn and Clarkson (2018) have in an extensive manner outlined various types of product development models and have described them as either procedural, analytical, abstract or management science/operations research models:

- *Procedural models* convey best practices intended to guide real-world situations
- *Analytical models* provide situation-specific insights, improvements and/or support which are based on representing the details of a particular design and development activity
- *Abstract models* convey theories and conceptual insights regarding the design and development process
- *Management science/operations research models* use mathematical or computational analyses of representative or constructed cases to develop insights into design and development

Further on, the models are categorised as operating on either micro-, meso- or macro levels:

- *Micro-level models* focus on individual process steps and their immediate contexts
- *Meso-level models* focus on end-to-end flows of tasks as the design progresses
- *Macro-level models* focus on project structures and/or the design process in a context

The study states that knowledge management models are predominantly *micro-level analytical models*, i.e. focusing on the individual process steps and their immediate contexts which provide situation-specific insights, improvement and/or support based on representing the details of a particular design and development activity.

2.8. Knowledge management in the equipment acquisition process

Research has also demonstrated the importance of using knowledge gained from earlier projects to eliminate future design weaknesses (Morgan & Liker, 2006). It is therefore relevant to examine the barriers of capturing and transferring maintenance-related knowledge from operations into the process of procuring new equipment and for future maintenance needs to be increasingly integrated. Bouwmans (2003) discusses barriers to knowledge management in the area of purchasing which are found in Table 1. As studies regarding knowledge management or re-use within purchasing or acquisition-related domains are rare, some of the barriers brought up in this section will by necessity be more general as the studies in question do not generally cover specific areas in an organisation. Thus, the following section will discuss general barriers and how they relate to those uncovered by Bouwmans (2003).

Table 1: Barriers to Purchasing knowledge management adapted from Purchasing Knowledge, (Bouwmans, 2003)

	Barrier summary	**Barrier details**
1	No clear definition of knowledge	Purchasers and/or purchasing managers are not aware of what information that categorises as knowledge and thus why knowledge should be shared
2	Purchasers are unaware of who owns which knowledge	One reason why knowledge is not shared within organisations is that purchasers do not know each other or are not aware of the knowledge possessed by a colleague
3	No incentive to share knowledge	Sharing knowledge is assumed only to be time-consuming and no incentives are in place to motivate the purchaser to share his/her knowledge

4	Geographically dispersed	Because departments and groups of large companies are often physically and geographically dispersed, purchasers argue it is difficult to share knowledge
5	Systems are not available or user friendly	Purchasers argue that available systems are in fact not available nor adequate or user-friendly
6	The content of systems is not up-to-date	Information is often not available in systems. Secondly, the information and knowledge are often ambiguous or not brought up-to-date
7	Purchasers do not possess the skills to use the systems	The organisation does not possess the administrative skills and/or lack an understanding of what data that should be entered into the systems
8	No time is available to share knowledge	Purchasers have no time available or do not take the time to share knowledge. Documenting their knowledge is often avoided because it is a time consuming task.
9	Transparency is threatening	Transparency in processes, contracts and supplier relations means that some flaws may be revealed. Purchasers are afraid to be punished or criticised for these flaws
10	Risk of becoming redundant	By sharing knowledge, purchasers are afraid of becoming redundant and therefore lose their jobs
11	Knowledge is regarded as power	Knowledge gives an individual or a group a certain position in the organisation. Individuals are respected for their unique knowledge and groups gain benefits that other groups within the organisation cannot achieve
12	Lack of respect for colleagues and their knowledge	A lack of respect results in less communication, interaction and openness and thus in less knowledge sharing
13	Knowledge is assumed to be unique	Purchasers argue that projects they are involved in are unique and thus sharing knowledge concerning these projects would be redundant
14	Knowledge is sensitive and confidential	Purchasers have the perception that their knowledge is sensitive and confidential. For example, contracts and relations with suppliers cannot not be shared

Many of the barriers are also mentioned by other authors outside of the purchasing area. For example, there are multiple authors claiming that trust and respect is essential for knowledge re-use, such as McNichols (2010), who covers cross-generational communication, specifically between baby boomers and generation X, in addition to Davenport and Prusak (1998), who cover the topic of learning organisations. However, this is questioned by Schacht and Maedche (2016), arguing that earlier research results on trust are outdated and that trust is much less of a barrier than before, partly due to the growth of the internet. Realising that these two former articles are either older or conducted on an older generation, the conclusions may be correct in each corresponding time or domain. On a similar topic, people assume knowledge is unique or regarded as power, Ardichvili et al. (2003) argue that a reason for ”hoarding” information is not because of selfish reasons, such as being the sole source of certain knowledge to assert the organisation needs you; but rather due to a fear of contributing information which is inaccurate or nonessential, and that fear of ridicule or criticism is a barrier to posting information on an organisation-wide system.

Further, problems with IT-systems are brought up by Chinowsky and Carrillo (2007) who outline the difficulties that come from utilising an IT-system which was not developed for the correct purpose. Thus, even though knowledge management and learning are not IT-issues per se, IT is essential for providing an infrastructure that allows for sharing and accessing knowledge. Another barrier mentioned by other authors is the lack of time for knowledge sharing (Davenport & Prusak, 1998; Wilkesmann & Wilkesmann, 2011). Both articles also mention space, which can refer to both physical space as well as digital space, such as e-learning systems, as a crucial component for successful knowledge transfer. Slack time is also reiterated as an important factor towards superior knowledge gathering and ultimately superior project performance (Haas 2006).

A definition of lessons learned, according to Project Management Institute (2017): ”The knowledge gained during a project which shows how project events were or should be addressed in the future for the purpose of improving performance.” Another definition of lessons learned, brought up by Weber et al. (2001), is used by the American, European and Japanese Space agencies as follows:

“A lesson learned is a piece of knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. Successes are also considered sources of lessons learned. A lesson must be significant in that it has a real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or eliminates the potential for failures or mishaps or reinforces a positive result.”

A similar definition comes from Walden (2012):

“Results from an evaluation or observation of an implemented corrective action that has contributed to improved performance or increased capability. A lesson learned also results from an evaluation or observation of a positive finding that has not necessarily required corrective action other than sustainment.”

The two latter also place focus on the need to acquire lessons learned in the form of best practices; not only looking where the project went wrong but also finding positive results which can be applied to other projects. Dülgerler and Negri (2016) describe how the process for developing lessons learned traditionally involves the three steps of:

1. Collecting, identifying and analysing lessons
2. Documenting, codifying and archiving lessons
3. Communicating, whereby lessons are disseminated to relevant groups of people

They discuss further how this is insufficient and requires two other phases: lessons need to be prioritised before they are documented, and they need to be assimilated by using a database. The authors also mention common pitfalls:

- Finding experiences can be difficult as people may not want to share their failures.
- The form in which recommendations are written often become too general and ”non-actionable” with no relevant instruction on how to implement the lesson. This is

supported by Milton (2010) and Walden (2012) who argue that advice should be specific by avoiding phrases that are too general without clear results.

- The vast number of lessons can create a database which is too time-consuming to navigate to find lessons relevant to the task at hand.
- Unless practised thoroughly, checking for earlier lessons learned may often be neglected at the start of a project, with the potential consequence that engineers become less inclined to contribute their lessons learned.

Regarding the last part of a traditional process, the communication part, it is similar to the KVC-step of dissemination, which is discussed with regard to lessons learned by Weber et al. (2001). They bring up different types of dissemination and the typical characteristics of each:

- Active Dissemination - The system dynamically notifies the user when it finds a relevant lesson in the context of an active process
- Passive Dissemination - Users need to actively search for info while the system itself remains passive
- Proactive Dissemination - Similar to active, but builds a model of the user's interface to predict when to notify the user with a relevant lesson
- Reactive Dissemination - Similar to a help-desk or help system
- Active Casting - Lessons are sent to profiles who could potentially use them
- Broadcasting - An example are bulletins which are sent to everyone in the organisation

Milton (2010) discusses two fundamental choices that impact how a system of lessons learned should be designed: deciding the degree of formal/informal system and whether the focus should be on connecting people or collecting lessons as described in Figure 13 below.

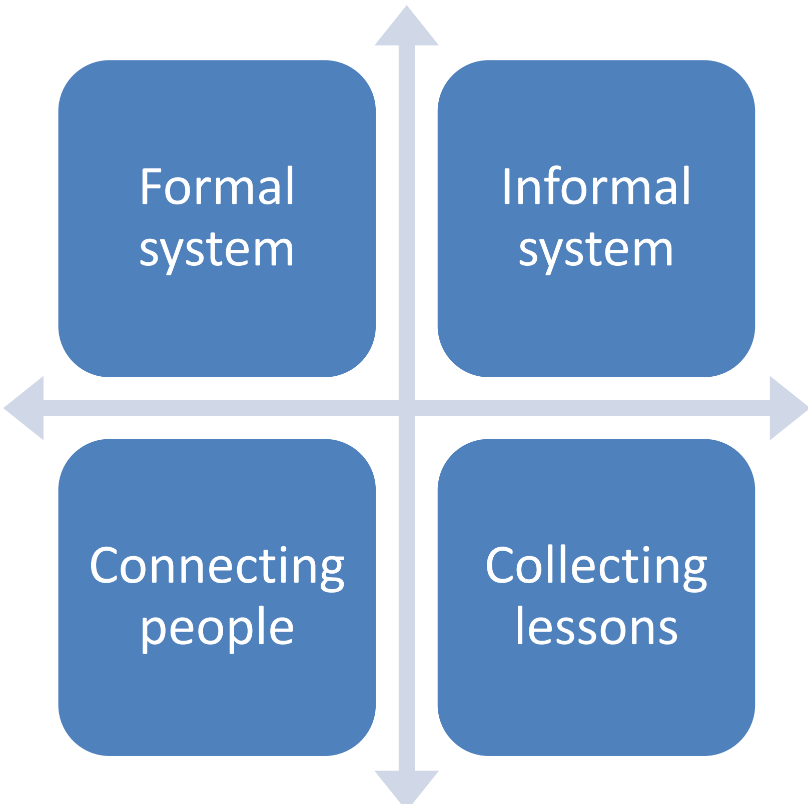


Figure 13: Two fundamental choices that impact how a system of lessons learned should be designed: deciding the degree of formal/informal system and whether the focus should be on

connecting people or collecting lessons, from Milton (2010)

This creates four approaches with different strengths and weaknesses of each approach. A formal collecting system could be difficult to fill with content but the content is easy to retrieve, whereas it might be easier to enter basic content into an informal collecting system but lessons might be missed, either from being uploaded into the system or being difficult to find. A formal connecting approach may be favourable in an environment in which problems are constantly changing but could be less appropriate in an environment where strict adherence to standards is required, a process normally connected to a more rigid updating practice. Finally, the approach of informal connecting is exemplified by social media, where it is easy to find discussions, questions and answers that may be beneficial to the organisation. However, it can be difficult to distinguish opinions or individual experiences from valid lessons, an approach which may not be appropriate for systematic knowledge sharing.

In summary, a ”blended approach” is recommended by Milton (2010), whereby the system utilises both connecting and collecting qualities. When it comes to formal and informal approaches, there needs to be a balance rather than a blend; a formal system running parallel to an informal system may cause confusion if the same lesson differs in the two systems. This is a point also argued by Powell (2001), who encourages informal knowledge exchange. The connecting/collecting dimension is linked to the important decision of whether the author should be anonymous or not; Weber et al. (2001) mentions anonymity as a way of finding more realistic lessons as there is less risk of consequences by sharing negative experiences. However, according to Milton (2010) there are benefits to disclosing the author which enables the reader to connect with the author if additional information on the topic would be needed. As previously mentioned, utilising both connecting and collecting approaches are recommended, requiring an author for each lesson. Thus, it needs to be carefully evaluated whether the identity of the author should be disclosed. Further, Milton (2010) presents advice on how to conduct lessons learned efficiently, for example:

- Schedule sessions on lessons learned at regular intervals throughout the project
- Use a moderator to share input from everyone but keep to the topic
- Write lessons with the reader in mind
- Ensure that documentation is easily accessible

When it comes to maintaining a lessons database, multiple authors mention the importance of verifying the lessons that go into the system. Dülgerler and Negri (2016) argue that the amount of lessons can become overwhelming as every stakeholder thinks lessons that improve the process within their area of responsibility are all-important; causing a wealth of ambiguous lessons that do not focus on the actual root-cause problems unless prioritised correctly. This is elaborated further by Milton (2010) and Walden (2012) who argue that quality assurance or review of the database of lessons learned is necessary. Also Weber et al. (2001) note the importance of validating the lessons for redundancy, relevance and correctness. Unless the database is maintained, there is a risk of making the retrieving of a lesson becoming a case of finding the ”needle in a haystack”, which may cause employees to be less inclined to use it. This in turn lessens the motivation of uploading relevant content into the database.

A tool used to capture and transfer knowledge is an Engineering Check sheet (ECS), as discussed by Stenholm et al. (2019); in essence a checklist of actionable and experience-based knowledge elements which consist of one or several *know-what's*, often accompanied by k*now-how's* and k*now-why's*, which detail how to perform an action and applicable circumstances. It is also beneficial to include references to other documents or people whenever necessary. An

ESC should also strive towards quality over quantity and be as condensed as possible as overly detailed descriptions can be confusing and difficult to assess. As for the merits of using ECS, Stenholm et al. (2019) found that inexperienced engineers in particular benefit from using it but found that it can be tedious to go through the documentation. It may also be beneficial for experienced engineers who use it as stress-relief to make sure all important pieces of knowledge are documented rather than relying on memory. It is also easier for an experienced engineer to go through an ECS as they usually only need to glance at the ”*know-what*” to get a sufficient overview. The case company has been in use in the case company, predominantly in the product development organisation,

Further, Stenholm et al. describe the steps of a knowledge management cycle: acquire, assess, apply, create, identify, refine, and disseminate, as well as factors which are important to achieve for a valuable flow of knowledge. Another important aspect of knowledge sharing is brought up by Powell (2001) who stresses the importance of an informal exchange of knowledge by running into someone in the hall or talking by the watercooler, giving people a chance to let someone know of a minor update or what went wrong in their latest project.

3. Research approach

In this chapter, the research approach to answer the research questions are described.

Several authors have discussed the need for design research to be scientific (Blessing and Chakrabati (2009) and how to achieve a sufficiently scientific level in this type of research. Research in the engineering design field is not only understood as a pursuit of scientific knowledge; it also pursues the goal of practically improving engineering design and practice (Eckert et al., 2003). Ullman (2003) states that an estimated 85% of product development projects encounters problems in cost, time management or by simply not functioning as intended which means the design process is worth studying to identify improvement areas.

Research approaches include plans and procedures for research that span the steps from broad assumptions to detailed methods of data collection, analysis and interpretation (Creswell & Creswell, 2018). Figure 14 presents the framework by Creswell and Creswell (2018) for research into the interconnection of worldviews, design and research methods.

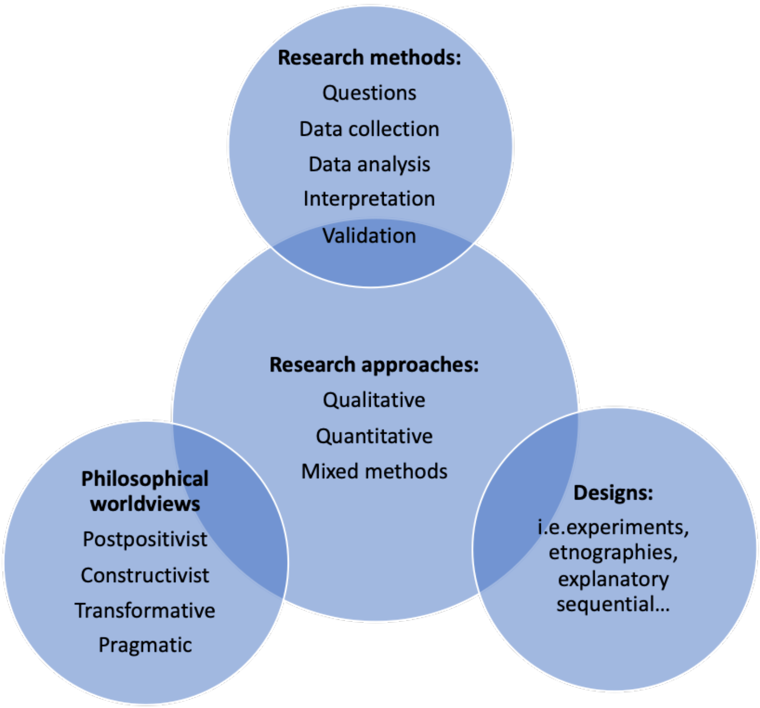


Figure 14: A framework for research - the interconnection of worldviews, design and research methods (Creswell & Creswell, 2018)

The decision on which research approach to use includes the philosophical assumptions the researcher brings to the study, procedures of inquiry (research designs) and specific research methods of data collection, analysis and interpretation. The selection of research approach is also based on the nature of the research problem, the researcher's personal experience and the audience of the study. This chapter explains the systematic way in which this research is performed, what worldview and research approach are relied on, and how the research questions are answered in the research projects, studies and appended papers.

3.1. Research methodology

To counter the critique of the scientific qualities of engineering design research, several researchers have suggested research approaches to guide researchers in the field. Among the most common methodologies applied is the Design Research Methodology (DRM) presented by Blessing and Chakrabati (2009), which this thesis has applied for the descriptive part, as described in Figure 15 below.

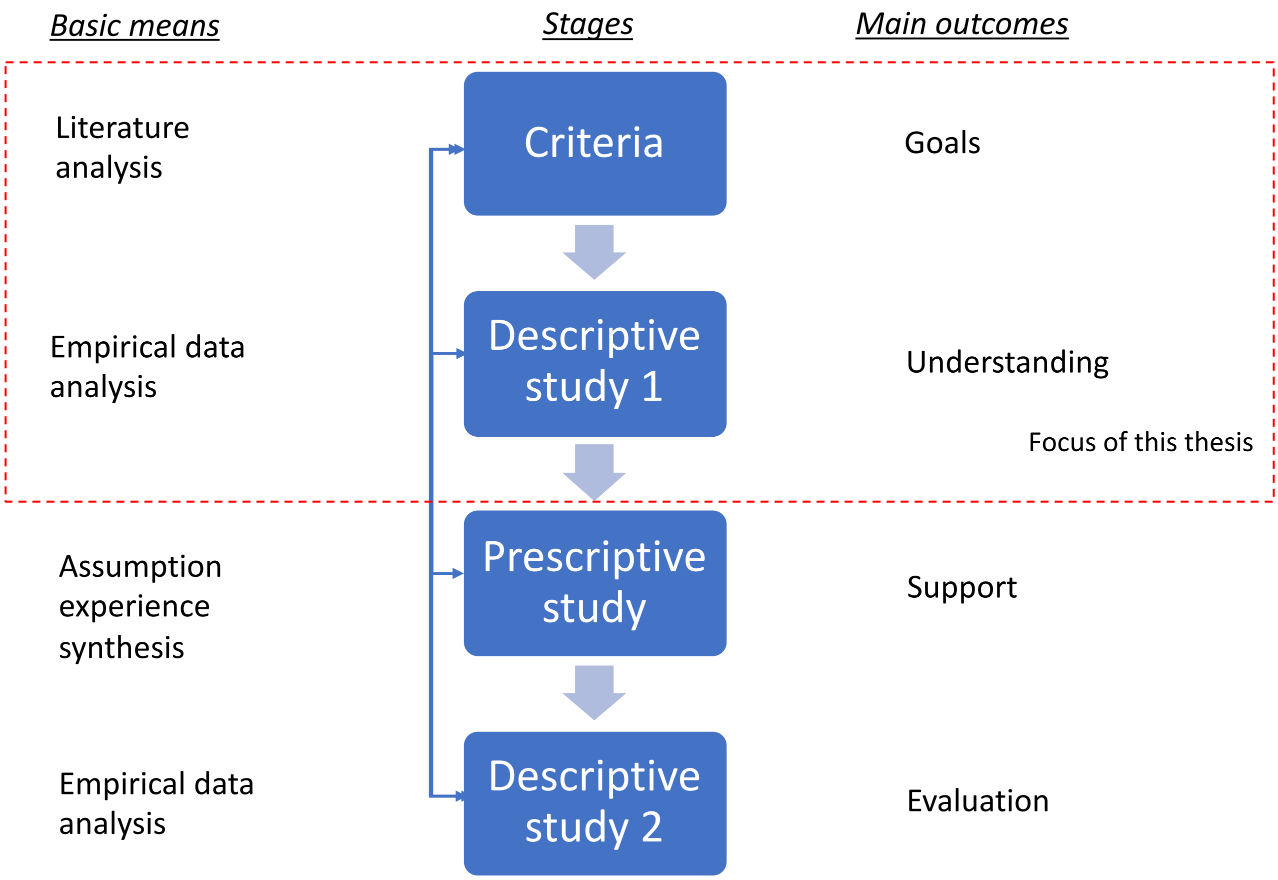


Figure 15: The DRM framework, from Blessing and Blessing and Chakrabati (2009). The red square is visualising the scope of this thesis.

3.2. Validation approach

As Isaksson et al. (2020) state: “How engineering design research can be validated in practice depends on the nature of the research that is being validated”. Le Dain et al. (2013) are proposing validation criteria as seen below in Table 2, with empirical research validation criteria:

Table 2: Validity criteria according to Le Dain et al. (2013)

Dimension	Empirical research
Truth value	Credibility
Applicability	Transferability
	Analytical generalisation
Neutrality	Confirmability

Credibility is validated by confirming with experts in the company, as well as confirmation in literature. Transferability is more uncertain; this study was performed in a single organisation, however, exploring several plants, projects and functions. Even so, findings may not be transferrable to other contexts. The analytical generalisation is secured by using established analytical models, such as cost deployment, knowledge barrier framework and activity theory. Confirmability is secured by the first two studies strictly using quantitative data from within the company systems. Confirmability in the third study, with only qualitative interviews, could be secured by using four projects for comparison purposes.

3.3. Theory building

Due to the nature of the research problem; a phenomenon which is characterised as a social process, with the research intention of formulating a model that explains this process, the success of the process and suggestions of improvements to the process, the grounded theory (Creswell & Creswell, 2018) is selected as the overall research method. In grounded theory, there is no initial hypothesis described and the approach is instead to investigate the data and define the models as the data are collected and analysed. To be able to answer the research questions, literature studies supported by case studies have been selected as research approach.

3.4. Literature analysis

As stated in the frame of reference chapter; the depth of the research problem lies in understanding the barriers to managing knowledge during the equipment acquisition process. The literature study was conducted by setting up search strings and categorising the results, as illustrated in Table 3. Thereafter the findings are further analysed.

Table 3; Results from literature review

	Search string	Total results	Article	Conference paper	Book chapter	Book
1	“Knowledge management” W710 (Purchasing OR Acquisition	413	200	162	18	4
2	“Knowledge management” W/10 (Purchasing OR Acquisition) AND NOT (”Knowledge acquisition”)	138	73	49	7	2
3	“Knowledge management” AND Acquisition AND NOT ”Knowledge acquisition”	1524	557	825	49	15
4	”Knowledge management” AND Procurement	234	95	113	6	4

5	”Knowledge management” AND procurement	234	95	113	6	4
6	”Lessons learned” AND Procurement	504	187	251	11	4
7	”Lessons learned” AND (”TPM” OR ”Total Productive Maintenance”)	5	2	3	0	0
8	”Lessons learned” AND (Procurement OR Acquisition) AND Automotive	14	1	12	1	0
9	”Knowledge management” AND ”Early management”	2	2	0	0	0
10	”Lessons learned” AND ”Early management”	10	6	1	0	0
11	Lessons learned” AND ”Industrial engineering”	196	43	138	10	2

3.5. Research approach – Mixed methods research (case studies)

Creswell and Plano Clar (2017) define mixed-methods research as studies that include at least one quantitative strand and one qualitative strand. Johnson and Onwuegbuzie (2007) state that “mixed methods research is the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g. use of qualitative and quantitative viewpoints, data collections, analyses, inference techniques) for the purpose of breadth and depth of understanding and corroboration. Figure 16 visualises how the mixed methods research was approached in this thesis.

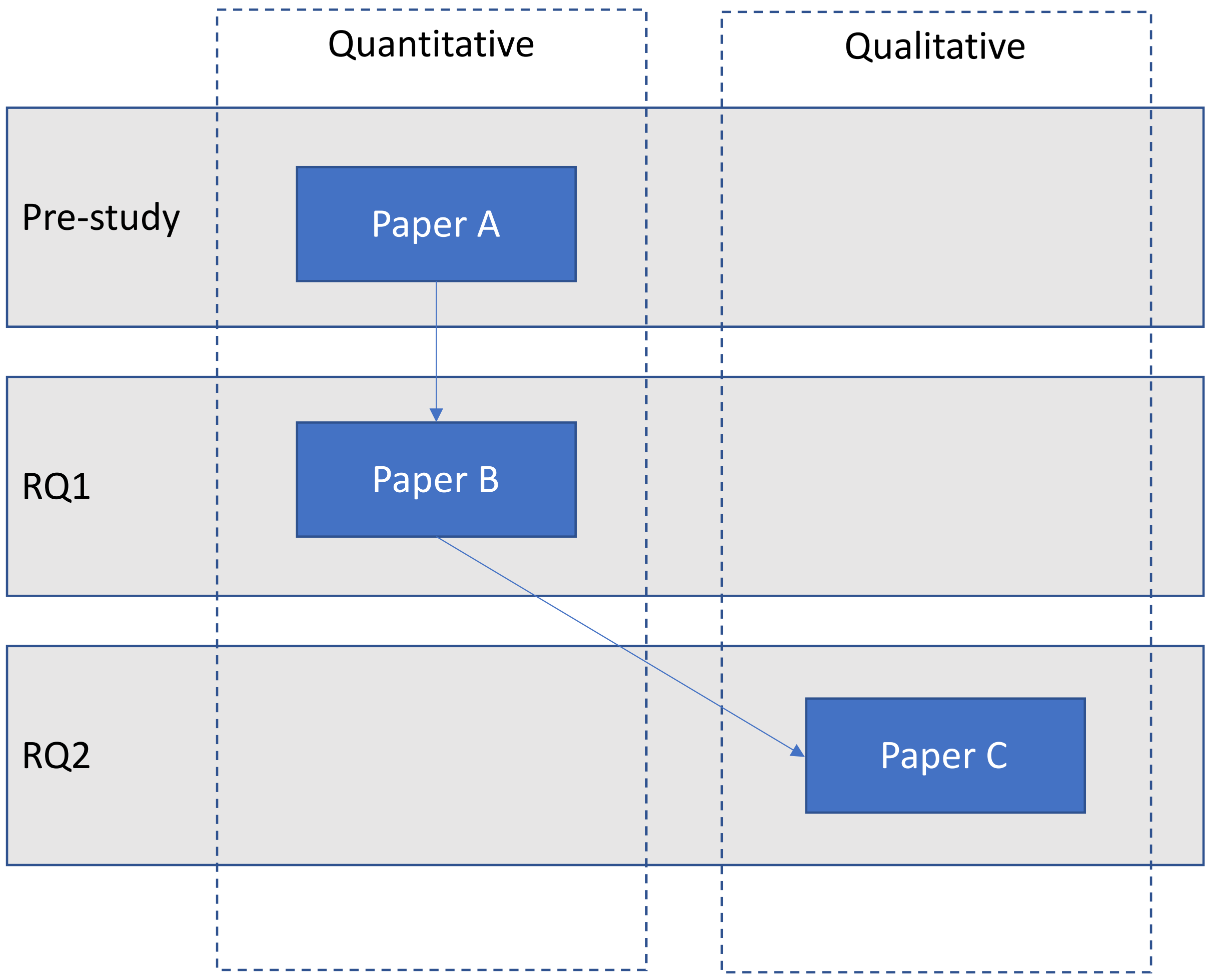


Figure 16: The mixed methods research approach applied in this thesis

Table 4 below describes the concept, attributes, variables, data, measurements, studies, analyses and data collection methods used in this study.

Table 4: Research methodology plan per research question

	Pre-study	RQ1	RQ2
Research question	Which major types of problems can be identified in an end-to-end production process within a large manufacturing firm?	What is the current capability of a manufacturing firm to address equipment breakdown issues already during the production equipment acquisition phase?	What are the barriers that prevent us from capturing, sharing and re-using equipment breakdown knowledge from production into the production equipment acquisition phase?
Concepts	End-to-end production process, problem types	Capability, maintenance issues, equipment design phase	Knowledge management barriers, production equipment acquisition phase
Attributes	Cost of problem types	Total cost of breakdowns due to design weakness over time	Twenty-eight barriers, activity theory
Variables	110 problem types	A. Total cost of breakdowns that are due to design weakness (time and spare-part cost). B. Year that the machines were bought. C. Life length of the machine (1-25 years)	Knowledge management: individual, organisational and technological barriers Activity theory: Instruments, subjects, rules, community, division of labour, object, outcome
Type of variable	Ratio, dependent	A. Ratio, dependent. B. Interval, independent. C. Interval, dependent	Nominal
Type of data	Raw, field, financial, empirical, objective, quantitative, secondary	A. Raw, field, financial, empirical, objective quantitative, secondary. B. Raw, field, secondary, objective, empirical, quantitative. C. Raw, field, secondary, objective, empirical, quantitative	Primary, subjective, analytical, qualitative, experimental
Measurements	Monetary for one specific quarter, Q1 2018	A. Monetary. B. Time. C. Age	Analysis towards the theoretical frameworks
Studies	Case study, field study, data study,	Case study, field study, data study,	Case study, field, study, interview study, retrospective

	retrospective longitudinal study	retrospective longitudinal study	longitudinal study, epidemiological study
Analysis	Quantitative, inductive statistics, comparative analysis	A. Quantitative, inductive statistics, comparative analysis, correlation analysis. B. Quantitative, inductive statistics, comparative analysis. C. Quantitative, inductive statistics, comparative analysis	Qualitative, phenomenology
Collection method	Cost deployment data from three plants for Q1 2018 in Qlikview and Excel	The data is available in the maintenance system in the case company (VMMS)	Interviews

3.6. Research methods and design: Data collection methods used to answer research questions

3.6.1. Pre-study: Data collection methods used

For the pre-study, to understand the main problems in an end-to-end production process, a retrospective longitudinal case study using field data was designed for a representative flow within the heavy automotive industry. The flow selected is a high-volume flow, involving three main plants all located in Europe. Figure 17 shows the value flow in the study.

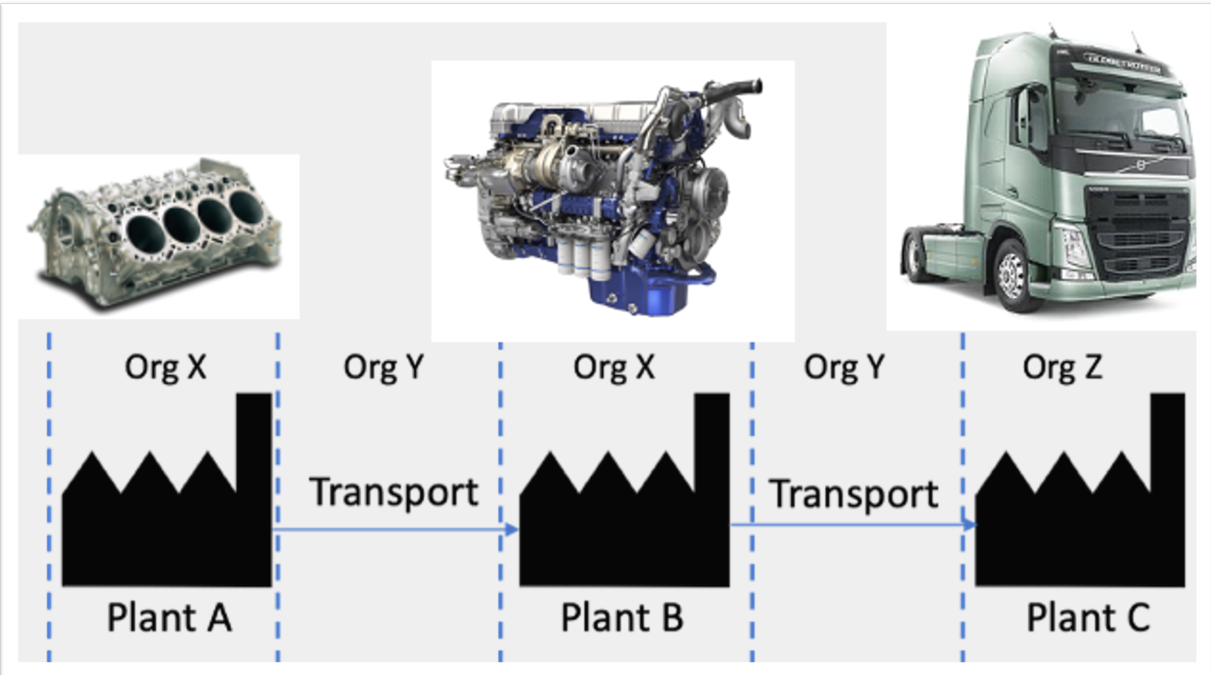


Figure 17: Visualisation of the value flow in the study

The selected case study covers the supply chain flow from raw metal to finished truck, thereby studying not only a limited part. A statistical method of inductive, comparative analysis is selected as the straightforward question is asked as to which loss is the largest? The academic value is that the method of calculation is not normally performed in an entire flow but today within individual plants which means that new statistical models have been used. A nominal factor needed to be developed to be able to compare costs. The types of industrial losses associated with production flows are to be used. To be able to quantify the impact of losses, the attribute is the cost of defined losses. The variables within the attribute are defined as 110 specific loss types each made up of ratio and dependent variables. Data characteristics include raw data and field data as well as financial, empirical, objective, quantitative and secondary data. The data are captured by financial departments in plants and logistics and reported in financial systems in the company.

The case company is using a method called cost deployment to quantify and visualise the main wastes and losses. This method has mainly been used within the perimeter of a plant but this study is testing the method on an entire flow between plants, from metal to finished truck. The research design entails a case study from Volvo Group Operations, following a product from metal scrap, that is cast, then machined, thereafter sent to assembly to become part of the engine and, finally, sent to a truck plant to become part of a truck. The research method is to collect already existing quantitative waste and loss data for one quarter (Q1 2018). The data represent the cost of the company for the loss, broken down to detailed levels to how much an extra step costs, how much a machine breakdown costs, etc. This data are consolidated each quarter, with one quarter equalling close to 100,000 data points. The data are mainly collected automatically but also manually during the operating processes, with about 60 systems for data collection per plant. The method is to use quantitative and inductive statistics with comparative analysis to analyse the data.

3.6.2. RQ1: Data collection methods used to answer the research question

For RQ 1, to understand the current capability of a manufacturing firm to address maintenance issues in the design phase, another retrospective longitudinal case study was designed using field data. As the pre-study found that maintenance is the largest problem for the company studied, the focus in RQ1 is to better understand the generation of the normally distributed maintenance costs. The first study was designed to understand whether the acquisition process is improving how to re-use knowledge by using quantitative methods. The study was evaluating the effectiveness of machine acquisitions and design by the impact on maintenance cost. For this study, statistics of inductive, comparative nature has been selected. The method has not been used in this way before as a measure of the effectiveness of the design process. The case study is performed in a large, high-volume plant with more than 1000 multiple-operation machines in subtractive manufacturing. The maintenance cost for machines that are only a few years old has been compared to machines that are at the end of their life-cycle, approaching 25 + years, in order to explore the impact of life-cycle thinking on maintenance cost. The case study is using empirical quantitative data analysis, comparing breakdown maintenance cost for 21 newly acquired machines during a five-year period of 2014 – 2018, to 120 machines approaching their end-of-life. The breakdown maintenance costs represents the cost of missed time in production, the hourly cost of a technician plus the cost of any spare-parts needed. The breakdown data are captured in real time or on the same day and are collected to a large extent automatically, as well as manually. The breakdowns are categorised into root causes but this article focuses on breakdowns due to design weaknesses, i.e. the component is not correctly designed or is causing another component to fail. The concepts used in the first study is the change in overall maintenance cost and design-related maintenance cost. The attributes are maintenance costs, including design-related maintenance costs, but also the years the machine was bought and age of the machine. The variables for maintenance costs include the costs for down-time, technician time and spare-part costs, which are categorised as ratio and dependent variables. The variables for the year the machine was bought and the age of the machine are categorised as interval and dependent variables. The data are categorised as raw, field, financial, empirical, objective, quantitative and secondary data. The analysis was quantitative and entailed inductive statistics, comparative analysis and correlation analysis of the data. The data were captured through the company's automatic maintenance system. The analysis method for this study was quantitative, inductive statistics, comparative analysis and correlation analysis, together with quantitative, inductive statistics and comparative analysis of the data.

The case company has been collecting improvement data on a detailed level for more than a decade. The data is collected in real time or on the same day and is aggregated for each quarter to analyse and prioritise improvement projects. Approximately 100,000 data points are collected, to a large extent automatically but also manually during operational processes. The data are then booked according to one of 110 categories. Within maintenance, there are six categories within to book the losses:

- Autonomous maintenance - breakdown due to faulty operator maintenance
- Human error craftsman - breakdown due to faulty contractor maintenance due to lack of knowledge
- Human error maintenance - breakdown due to faulty professional maintenance due to lack of knowledge
- Human error operator - breakdown due to faulty operation by the operator due to lack of knowledge
- Professional maintenance - breakdown due to faulty or not performed professional maintenance
- Design weakness - breakdown due to faulty design of machine

The final factor, design weakness, is the most relevant root cause to be investigated for this thesis as design might avoid a problem rather than solving it. If this category of problems can be fully understood, the cost of adjusting problems in production could be reduced. This category is capturing the maintenance problems that occur in production related to machine design. For this case study, breakdown data is collected for 21 new machines during a five-year period between 2014 and 2018 and compared to breakdown data for existing around 1,000 machines. The 21 machines have been continuously purchased in 2014 and their cost of maintenance was evaluated during five years onwards.

3.6.3. RQ2: Data collection methods used to answer the research question

For RQ2, a complementary qualitative study was designed by incorporating lessons learned from the pre-study and the RQ1 study and focusing on how the reduction of professional maintenance losses in production is addressed by efficient knowledge management during machine acquisition.

This retrospective longitudinal and epidemiological case study is a field study based on interviews and investigates the industrial system engineering design from this perspective. Four cases were studied (see Figure 18) in which the organisation already had a specific machine and bought another of the same type. In theory, the knowledge of machine problems should affect the buying of a new machine to ensure the same problems do not occur again. The barriers of capturing and transferring maintenance related knowledge from operations into the process of procuring new equipment from suppliers are investigated. Literature studies on the topics of lean thinking, maintenance, knowledge management and early equipment management were conducted. Case studies used interviews during which the reliability of the data was enhanced by using a pre-set interview guide. Each interview was performed in pairs, recorded, transcribed and then reviewed by a third person.

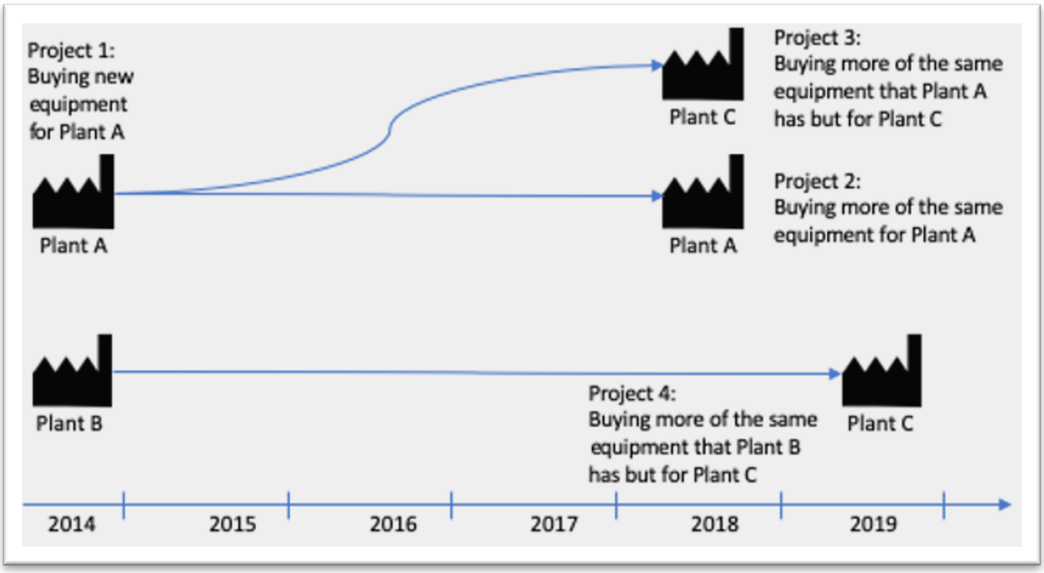


Figure 18: The four studied projects

Validity was enhanced by using senior business experts to secure relevance. To strengthen both validity and reliability, triangulation was used (qualitative data, review of internal documents and review of literature). The concepts used for this study included maintenance knowledge during the acquisition process, with the attributes of capture, share and re-use of knowledge. The variables were the 28 barriers to knowledge management (Riege, 2005) with individual, organisational and technological aspects, as well as the framework of activity theory for organisational learning (Engeström, 2000), with the variables of instruments, subjects, rules, community division of labour, objects and outcomes. For both attributes, the variables were nominal and the type of data was primary, subjective, analytical, qualitative and experimental. Phenomenology was selected as the analytical method for this specific study, as the purpose was to capture the human experience of the process as a form of life-world theory. The analysis methods selected were qualitative and phenomenological.

4. Results

This chapter presents the findings from the appended papers which are used for the analyses to answer the research questions.

4.1. Summary of appended papers

The main contributions of this thesis are published in three academic publications appended in the second part of this thesis. The findings in Paper A lead to the research motivation within the research aim. A summary of relevant parts of each publication follows below.

4.1.1. Paper A: Visualising wastes and losses in automotive production flows (across multiple plants and organisations) for increased accuracy in improvement prioritisations

To make sure the research of this thesis and onwards would focus on a real-world industrial problem, a pre-study, documented in Paper A, was performed to identify the costliest production disturbances experienced by the case company. A new method, end-to-end cost deployment, was tested to identify the most significant issues. The pre-study showed that equipment breakdown within the maintenance field was one of the most expensive factors. From that result, the rest of the research was addressing the equipment acquisition process and the community performing this process.

Conclusions Paper A: Equipment breakdown is a significant cost factor for the studied process, regardless of the size of the organisation or complexity of the product

4.1.2. Paper B: Evaluating the effectiveness of machine acquisitions and design by the impact on maintenance cost – a case study

The focus of Paper B was to compare the evolution of equipment breakdown cost during the life-time of 25 machines in a single plant and compare this cost to machines that were newly acquired to machines nearing their 25 year end-of-life. The assumption, supported by theory (Deighton, 2016), is that the cost of equipment breakdown should be decreasing during the early life of a machine. However, the study showed that the breakdown cost was much higher, and increasing rather than decreasing, than expected for recently acquired machines that actually had higher breakdown costs than machines nearing their end-of-life.

Conclusions Paper B: In contrast to theory, the equipment breakdown cost per machine increases instead of decreases during the initial phase of the life-cycle. In addition, in contrast to design process ambitions, the new machines had higher levels of maintenance cost than end-of-life machines. Finally, in contrast to theory, the design weakness share of maintenance problems stays on a plateau rather than decreases during the initial phase of the life-cycle.

4.1.3. Paper C: Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions

Paper C sought to understand, via interviews in four projects where the same equipment was acquired once more, the barriers to how knowledge from current production disturbance in terms of equipment breakdown cost was fed back to the equipment acquisition process. The study found that the barriers mostly existed along the individual and organisational dimensions and less along the technological aspect.

Conclusions Paper C: The main barriers to capture, share and re-use knowledge related to the acquisition of production equipment when focusing on maintenance were identified for the case study. The main barriers mostly existed within the individual and organisational dimensions and less in the technological dimension.

4.2. Paper A: Visualising wastes and losses in automotive production flows (across multiple plants and organisations) for increased accuracy in improvement prioritisations

The purpose of this study was to ensure that the continued research focused on a significant industrial problem area. It was at the same time a test to explore new ways with which to identify, quantify and visualise losses to correctly prioritise improvement efforts. This paper tests the potential of collecting data through the entire supply chain where several plants and operations are involved. This study was performed in collaboration with three plants and one logistic provider. An important purpose of the paper was to identify the main loss along an extended supply chain and make it comparable regardless of size of the plant or the complexity of the product.

The data across the entire flow is converted into an eleven-litre cylinder head equivalent by using the normalisation model. The results are visualised in Figure 19; the data is normalised to be comparable regardless of the size of plant or size of product. The bars differ depending on whether the observations are normalised or not. The removal of factors stemming from the size of the plant and share of production volume, the chart below gives a more accurate picture of the loss distribution for *a specific part*.

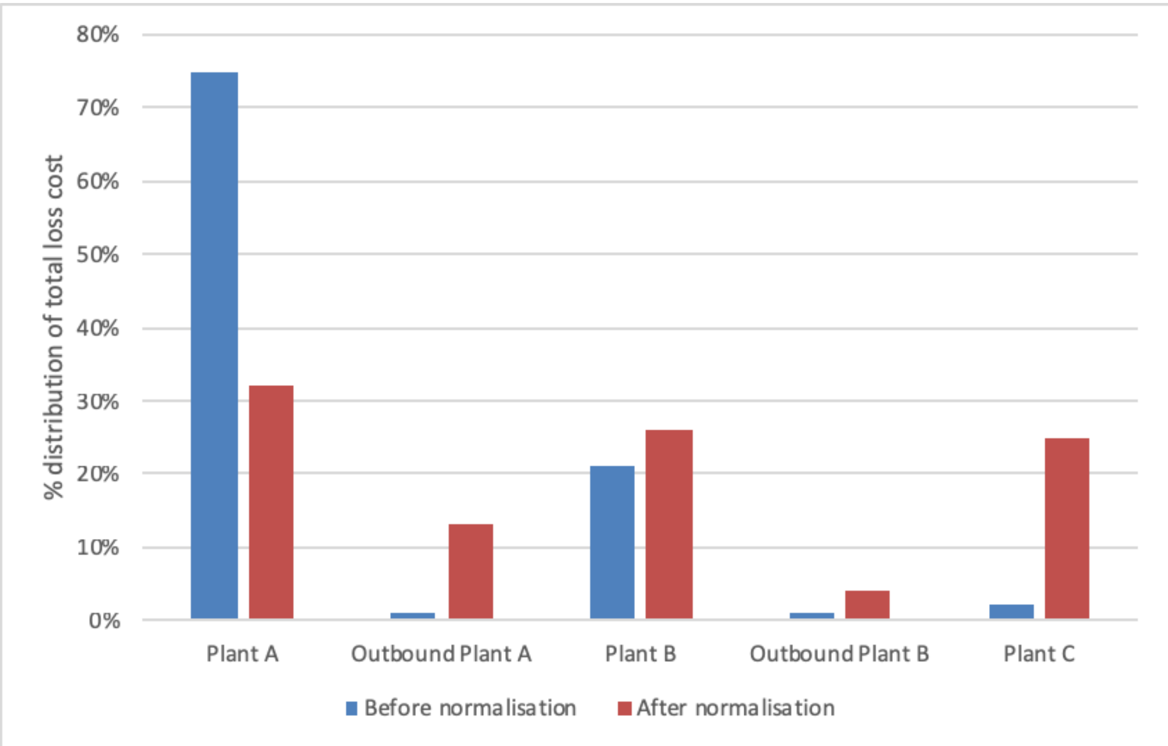


Figure 19:Comparing the distribution of total cost loss before and after normalisation per step in the process

By using this normalisation factor, it is possible to consolidate the losses from all plants and transports in-between and obtain a meaningful visualisation of losses during this entire flow which is visualised in Figure 20. The graph visualises the consolidated top eight losses for this particular flow within and between three plants. Two losses were considered one-timers and are not part of the graph.

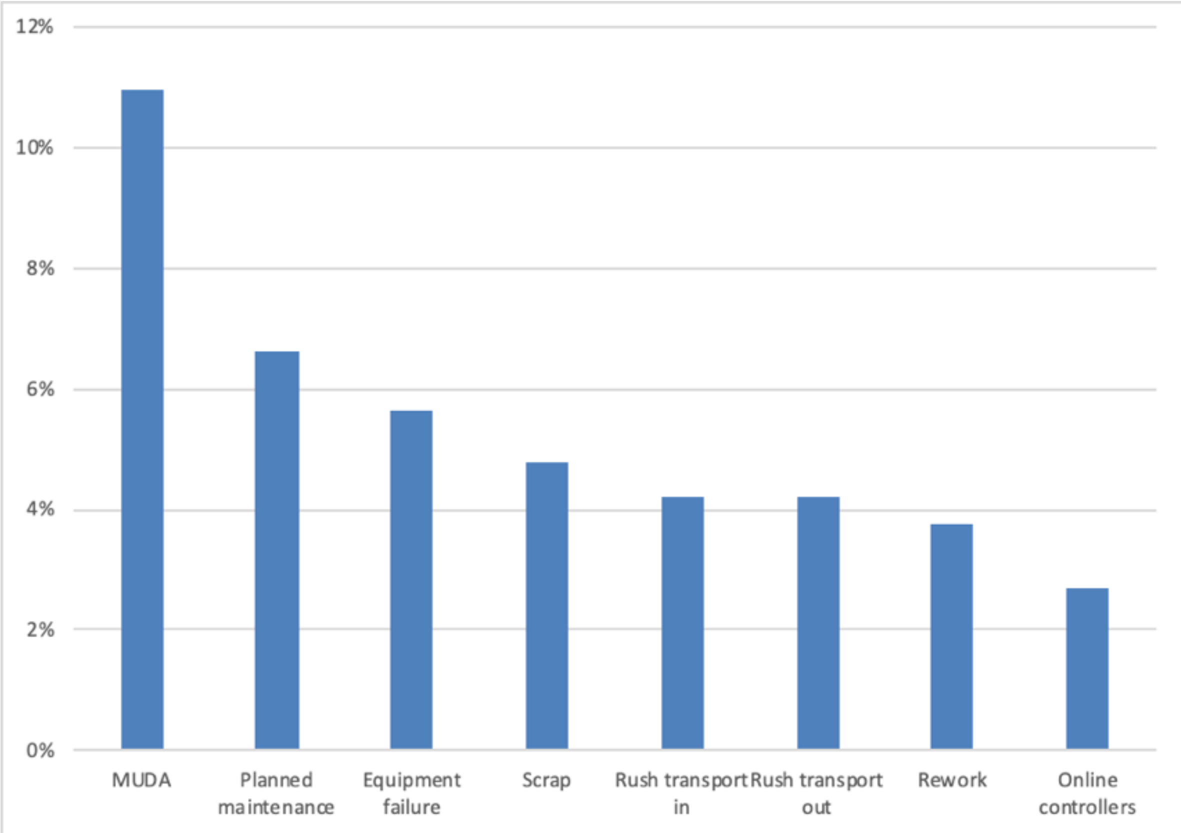


Figure 20: Top eight costs of losses in the supply chain flow using normalised data. Two losses were considered one-timers and are not part of the graph.

The profile corresponds to the assumption that since all sites are labour-intensive, non-value adding activities performed by operators (sometimes referred to as MUDA) would be a significant part of losses. Furthermore, this is at the same time a part machined with advanced equipment which makes maintenance losses natural. This study confirms this assumption as well. The top loss is non-value adding activities by operators, the second highest loss is caused by planned maintenance and the third highest loss is from equipment failure. For cost deployment methodology, the top three are to be assigned resources to initiate improvement and loss reduction activities. Thus, this result is on par with the research question stated and cost deployment methodology. These results provide the basis for recommendations to address the top losses. These top eight losses correspond to 43% of total losses identified which shows that by focusing improvement efforts on the top losses, total loss costs should be reduced significantly. Another finding is that even if the logistics flow only captures the cost of rush transports and not other logistic-related costs, both in- and outbound rush transports are among the top eight losses.

When the graphs are compared, in Figure 21, it becomes clear that when the data is compensated for size of plant and complexity of product, the loss profile for the cylinder head equivalent changes. The data show that when identifying major losses for a specific product this method can be used.

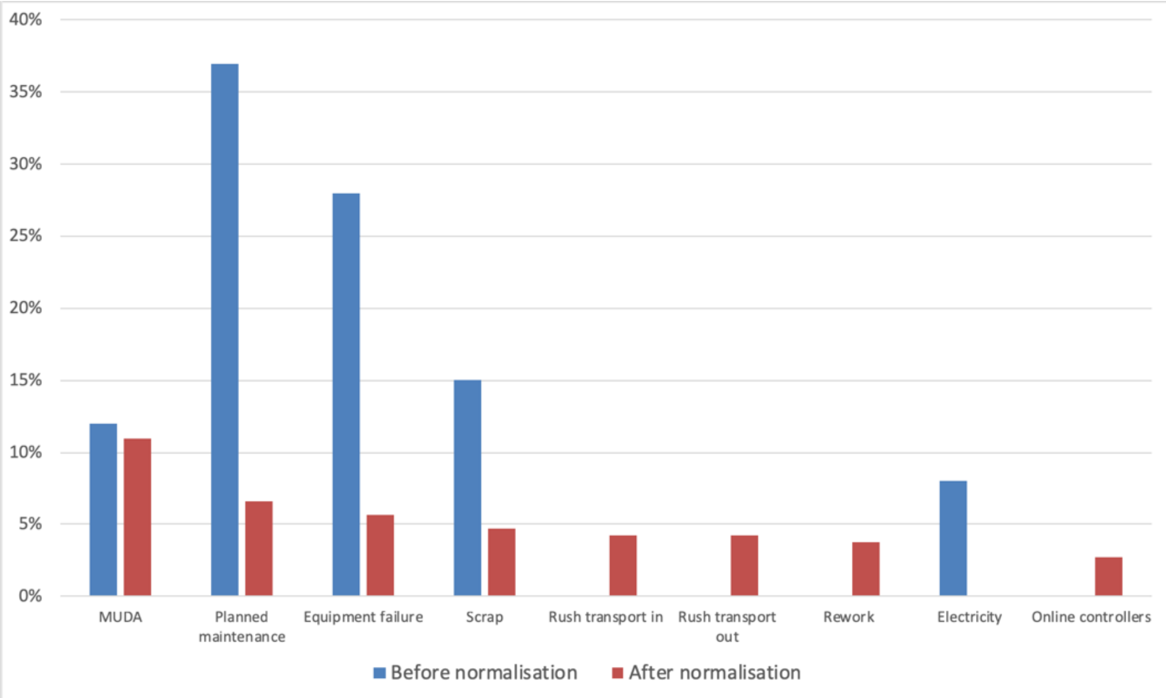


Figure 21: Comparison of loss data before and after normalisation. Specifically planned maintenance shows a large reduction through normalisation together with equipment failure and scrap.

4.2.1. Conclusions

Paper A shows that maintenance is a significant cost factor for the process studied, regardless of size of the organisation or complexity of the product, as described in Figure 22.

Figure 22: Maintenance losses are a significant contributor to the top losses

4.3. Paper B: Evaluating the effectiveness of machine acquisitions and design by the impact on maintenance cost – a case study

4.3.1. Purpose

Since maintenance losses were identified as a main contributor of production cost study 2 was designed to evaluate the engineering contribution to maintenance cost.

4.3.2. Results

Figure 23 shows the maintenance cost evolution, both in absolute terms and in percentage increases every year during initial phase of the life of a machine, the expected lifetime of which is assumed to be 25 years. Year 0 is the year when machines were purchased and as described below, the maintenance cost was increasing each year. For confidentiality reasons, the costs are masked to only show relative increases. Figure 23 shows that the maintenance cost is increasing by 59% from year 1 to year 2, by 12% between year 2 and year 3, and by 18% between year 3 and year 4.

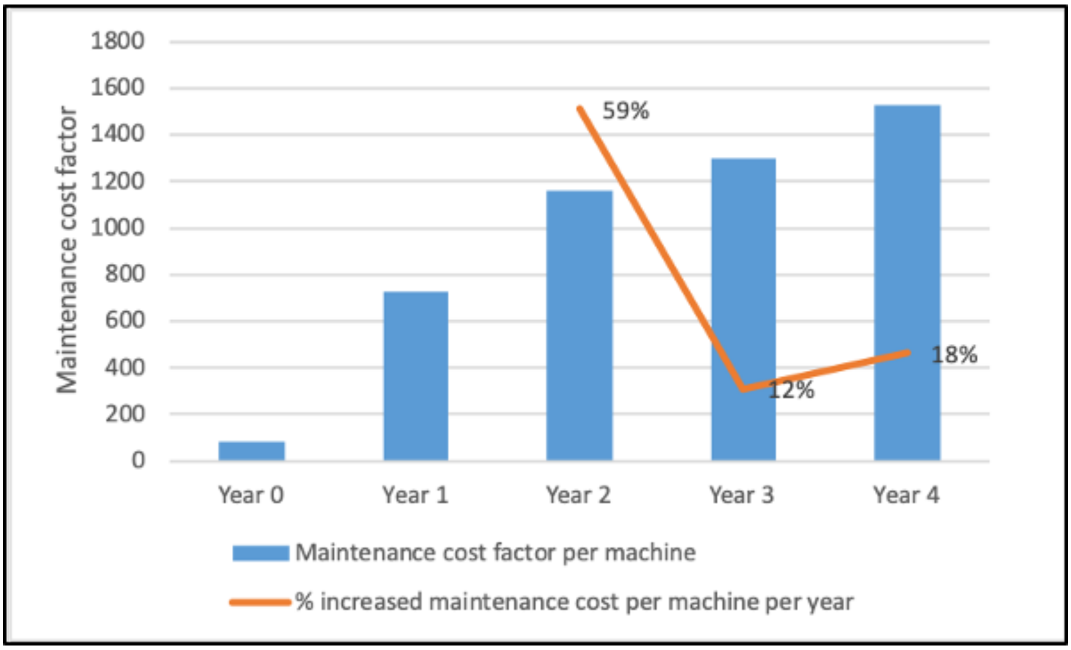


Figure 23: Maintenance cost evolution for the initial life of the purchased machinery; absolute numbers and the relative increase per year. A cost factor is used for confidentiality purposes.

In Figure 24, the maintenance cost per machine in the initial phase of the lifetime is plotted together with the maintenance cost for machines that are being phased out and compared to the bath-tub curve showing that the data are not following the expected evolution in terms of component reliability. The bath-tub curve is chosen to illustrate the profile of the curve. The graph indicates that old machinery, close to end-of-life, are performing better in terms of maintenance cost per equipment than recently purchased machines.

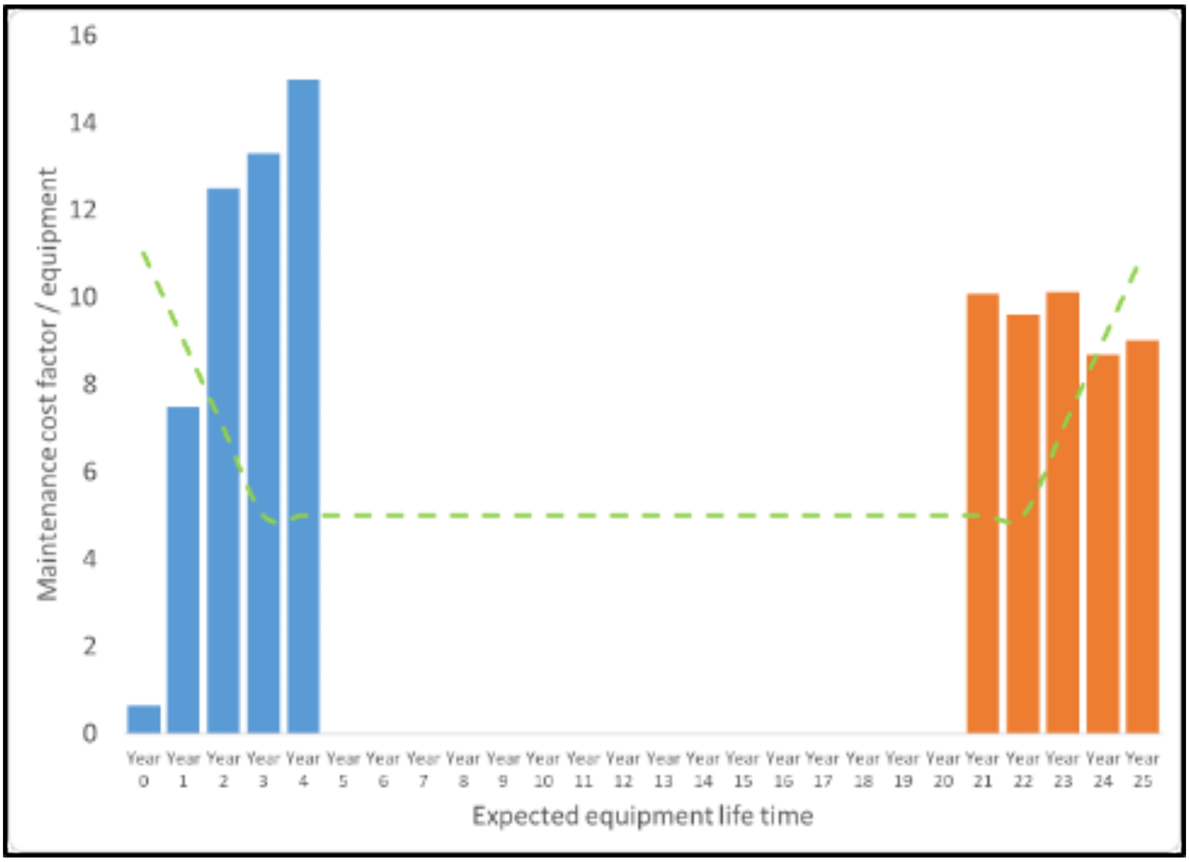


Figure 24: Maintenance cost data for the initial and end phases of the life-cycle, plotted against the theoretical bath-tub curve regarding reliability of components and machinery

To better understand the impact of design on maintenance cost, Figure 25 illustrates the evolution of design weakness as the root cause of maintenance cost. The breakdowns due to design weakness are increasing the first three years and are thereafter on a more stable level. Further, the share of maintenance breakdowns due to design errors continues to be between one quarter and one third of all breakdowns. Design errors should normally be detected during the early stages of operations and then eliminated by adjustment. The data below are following that theory initially but are then staying on a plateau without further reduction and are still contributing a significant share of the total number of breakdowns.

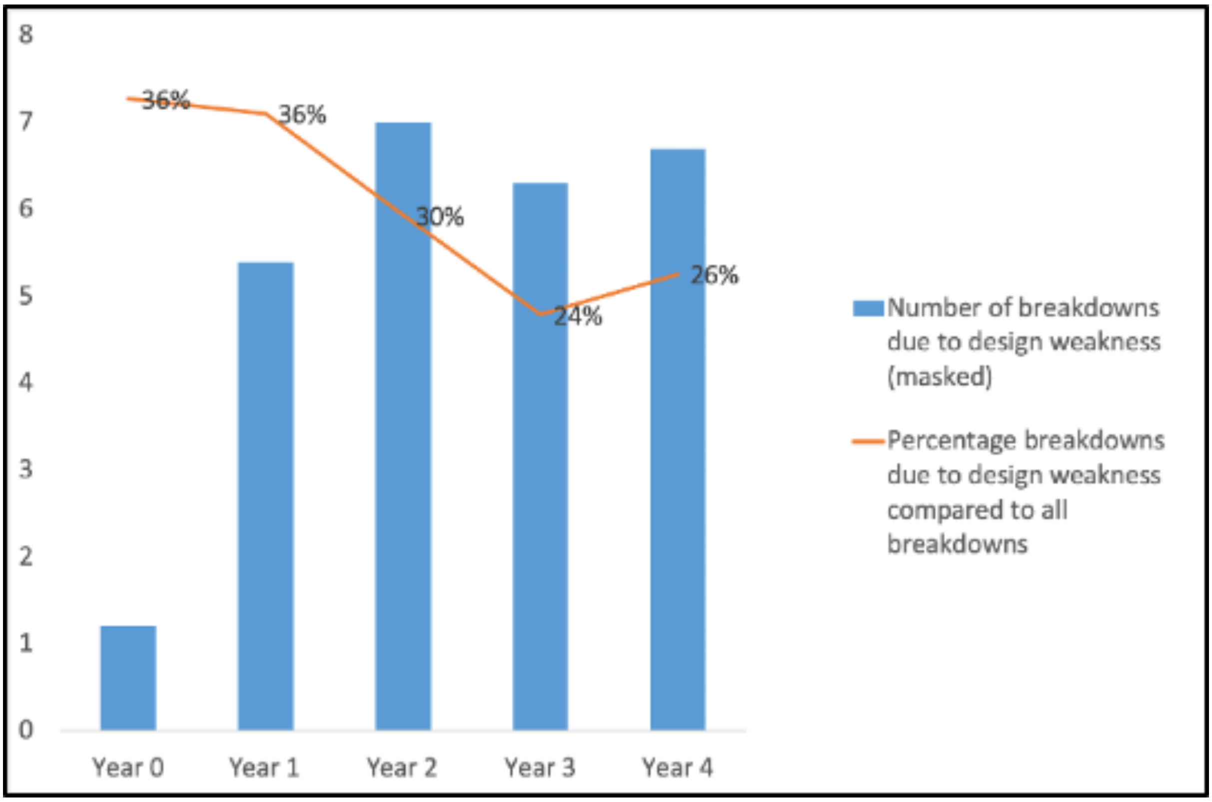


Figure 25. Comparative occurrence of breakdowns due to design weakness over years in production

4.3.3. Conclusions

In Paper B, the contribution from maintenance into circular economy was explored. Data from the study show three major findings:

- In contrast to theory (Deighton, 2016), the maintenance cost per machine increases instead of decreases during the initial phase of the life-cycle
- In contrast to design process ambitions, new machines feature higher levels of maintenance cost than end-of-life machines
- In contrast to theory (Deighton, 2016), the design weakness share of maintenance problems stays on a plateau rather than decreases during the initial phase of the life-cycle

4.4. Paper C: Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions

4.4.1. Purpose

To complement the quantitative studies of Papers A and B, a qualitative study was designed to understand the barriers to capture, share and re-use knowledge related to the acquisition of production equipment from a maintenance perspective.

4.4.2. Results

Equipment acquisition is called Early Equipment Management (EEM) by the case company. Plant A <u>defined</u> EEM as being a structured framework for procuring equipment by using previous experience. Three respondents mentioned that it was a process during which lessons learned from previous projects were to be included. All respondents described EEM as a structured process for procuring equipment. As one interviewee stated: "It is a good framework with which to tell you what to do and when to do it. It is a way of working that I think functions quite well".

In Plant B, EEM was defined as a structured framework through which to get improvements in new equipment. Furthermore, all of them described it as a structured process for procuring equipment. Only one interviewee stated that working with EEM presented an opportunity to obtain inputs for improvements. "For me, the principle of EEM is that when we are in the process of buying a new machine, we look at previous projects for any improvement points we can incorporate in this purchase".

In Plant C, EEM was defined as a structured framework for procuring equipment with the highest possible availability involving different functions. Only one respondent described EEM as a process for focusing on longevity, "the philosophy is to find out how to maintain your equipment with the highest level of availability possible and minimising the downtime, that is what EEM truly is". The respondent also expressed a concern about a lack of understanding of the EEM philosophy among colleagues. "Most people don't understand EEM but believe in the old form of preventive maintenance when a schedule for tasks is set in concrete. Now we are in a more competitive situation and need to be able to get as much available time as possible for production".

Regarding the EEM objective, Plant A focused on satisfying the Production Department, referred to as the customer, by delivering improved equipment. Indicators as "reliability" and "availability" were often mentioned as measurements of better equipment. A Project Manager specifically stated that "the project should meet the targets in terms of cost and performance in addition to other values, such as environmental, safety and ergonomic aspects".

Plant B instead focused on delivering equipment without disturbances in line with expectations and minimising risk. A respondent stated that the objective was for equipment to perform better as a result of time invested in making sure that the project had captured all knowledge and experience. An observation was that all interviewees mentioned their specific project as the objective; not the success of all projects from a systemic point of view, in literature defined as the organisational knowledge value stream.

Plant C mentioned that the objective of EEM was to include different requirements in all the departments, as well as delivering better equipment. The electric maintenance technician defined better equipment as having more up-time and less down-time.

When talking about the challenges of EEM, all three plants found the high workload or limited amount of time challenging. Plant A found competence a challenge, specifically how to know what competence to include in the project in order to achieve success. "The main challenge is to obtain a clear specification from the requester who has hopefully the competence to know what he or she needs, which is not always the case". Regarding the time aspect, an individual in Plant A stated that "we are rather conservative as we do not always have the time to test new technologies or new suppliers". Several personal aspects were also mentioned. "To achieve a successful project, you need not only competence but also engagement and commitment from the people involved".

Plant B found the lack of resources and competence restrictive. As a respondent stated, "We have the processes described very well but the trigger to buy a machine is often late which means that the entire purchase is pressured". Another comment was "this was very frustrating in the beginning but as I learn more, I realise how difficult it is for everyone to make the necessary decisions on time”.

Individuals in Plant C found the high workload difficult in addition to making other people in the organization understand the philosophy. A maintenance representative described one of the main challenges: "Project Managers must be on time and under budget which is their main task. But that collides with the holistic perspective and with trying to make this the best machine possible.". The respondent described the main challenge as being on a mission, making others understand the philosophy. The respondent also described the conflict between the traditional view of a project, being on time and budget, and the holistic view of EEM.

The interviews illustrated that several process tools were used in order to secure that the right knowledge was brought into the project. A majority of interviewees described how they also performed other activities, such as study visits, benchmarking and training, in addition to the process stated. Project engineers involve operators and maintenance technicians by engaging them in creating a list of improvements. Several interviewees described a lack of knowledge of EEM and the process of capturing knowledge and experience. It was stated that the level of knowledge had decreased in past years and that it was difficult to find appropriate knowledge. Table 5 shows the methods used to capture knowledge as inputs to the EEM process and the type of knowledge assimilated.

Table 5: Tools that are used in the case company to capture and transfer knowledge.

Tool	***Knowledge type***	***Plant A***	***Plant B***	***Plant C***
Emergency work order (EWO)	Explicit	X	X	X
Human Error Root Cause Analysis (HERCA)	Explicit			X
White book	Explicit		X	X
Industrial Project Assurance Plan (IPAP)	Explicit	X		
Technical specification	Explicit		X	
Scope of supply	Explicit	X	X	
Operators' list	Explicit	X		
Benchmark	Implicit	X		X
Study visit	Tacit	X	X	
Training	Tacit	X	X	X

Regarding the barriers to effective knowledge management, a few aspects were specifically mentioned. For example, on the organisational level, when asked how knowledge was captured for the next machine to be bought, a respondent stated “There is no way of capturing this other than my saying to my colleague that that specific component is very difficult to maintain. If we ever buy this machine again, I would speak up”. Others stated that knowledge was captured at the initiative of individuals as opposed to on a corporate system level. “We asked for volunteers among some of the younger engineers whether they wanted to shadow the process”. From the technological point of view, it was stated that the systems were perhaps not built up in the most useful way for engineers: “Nowadays, we have all requirements in a single system; it would be beneficial to have a requirement list for maintenance, another one for safety, and a third for quality, etc”.

Another example from a technological perspective was regarding documentation: "We received the information too late and when we received it, we discovered that is was sorted according to the wrong structure". From an organisational perspective, an interviewee stated that "Fifteen years ago, we had more skilled people than we have today. Either they have left the company or have new roles within the company. We have lost a lot of competence". This was supported by another statement: "A topic within my area of expertise has been operational competence. A key individual retired and we didn't think about transferring that knowledge because the process was working. When we started to get problems, we didn't have anyone who could solve them. The solution was to buy the competence externally". Several respondents demonstrated that competitiveness was not a big issue, neither internal nor external; there seemed to be low barriers for them to visit external partners or plants for advise. "We heard another company bought the same machine, so we went to them to have a look". Some lack of trust in the credibility of knowledge of others was demonstrated. "We used other oils than advised by the supplier and had a lot of problems". Table 6 illustrates the most frequent barriers that were raised by the respondents.

Table 6: Identified knowledge barriers in the study

Individual	**Organisational**	**Technology**
Time	Strategy	IT support
Awareness	Directions	
Explicit vs tacit	Support	
Capture	Low priority	
Trust	Infrastructure	

4.4.3. Conclusions

Paper C has identified the main barriers to capture, share and re-use knowledge pertaining to the acquisition of production equipment for maintenance. The main barriers were within the individual and organisational dimensions and less in the technological aspect. In the individual dimension, the main barriers were identified as a lack of time to work with knowledge management, a lack of awareness that it could be important, a lack of capability to transform the knowledge from tacit to explicit and, finally, a lack of trust in the knowledge stored. In the organisational dimension, the main barriers were identified as a lack of strategy from a corporate perspective on how to address knowledge management and hence a lack of directions and support from management to focus on it. It was perceived as a low priority within the organisation. Finally, a lack of infrastructure was identified as a barrier to actively working with knowledge management from an organisational perspective.

5. Analysis – answering RQs

In this chapter, the research questions are further evaluated and reflected upon as a first response based on the findings derived in the studies reported in Paper A, B and C.

5.1. Pre-study: Which major types of problems can be identified in an end-to-end production process in a large manufacturing firm?

All concerned plants had a well-established process of collecting data during Q1 2018. However, while capturing data, various levels of precision and dialects in loss stratification were evident. For the flows between sites, only data regarding rush transports were captured, not potential losses of packaging, waiting, wrong parts etc. A finding was the lack of a unified usage of definitions as different plants used different templates and formats to categorise losses and associated costs. There was also evidence of language barriers as the plants categorised losses in their local languages, leading to barriers in standardisation as knowledge sharing mechanisms failed to facilitate seamless knowledge transfer.

Performing loss cost analysis should not impact the daily work of manufacturing personnel. However, as this study highlights, changes to standardise the way in which data is collected and stored during manufacturing are necessary. These changes will to some extent affect people working in manufacturing, but they will also provide the benefit of getting up-to-date data collection procedures. The use of losses can further be helpful to prioritise bottlenecks and provide real-time and relevant data for improving the production system.

The understanding that production is a network of several interconnected manufacturing plants and that losses can be measured within the entire production network enable management to prioritise improvement projects optimally. Previously, there was a risk that manufacturing plants were sub-optimal and potentially reduced performance across the complete manufacturing network.

The ability to weigh value against manufacturing cost within the whole production system further reduces the risk of focusing on the wrong priorities as the ratio of value to manufacturing cost can be monitored across plants. By using this data driven method with strong visualisation for prioritisation of improvement efforts, the company studied has been able to deliver savings on world-class levels for almost ten years. By expanding scope and not only looking plant-by-plant, the potential is now even greater.

5.2. RQ1: *What is the current capability of a manufacturing firm to address equipment breakdown issues already in the production equipment acquisition phase?*

Exploring the contribution from maintenance into circular economy, data from the study is showing that maintenance of new machinery continues to be a problem for the case company and could possibly also become an increasing problem. This finding is supported by Figure 23 in which the maintenance cost is increasing by between 59%, 12% to 18% each year during the initial life of the machine. To evaluate the effectiveness of the acquisition process, data from Figure 24 shows that machines purchased recently have a higher maintenance cost factor; in year 4 the factor was 15, but the old machines that are nearing their end-of-life have a maintenance cost factor of around 9. Figure 25 is also investigating the effectiveness of the acquisition process; in year 4 of the life of the machine, maintenance problems related to design issues were still 26% of the total number of breakdowns. The findings supported the theories that the design process was becoming less effective; but they could also mean that the machines purchased recently are more complex to operate and maintain. Data are showing that design weakness, i.e. a problem with the machine due to its design is on a high level and continues to be on this level.

There could be numerous reasons, for example increased workload of engineers, increased complexity of the machines or increased complexity and globalisation of the supplier base. Consequently, there is an opportunity for increased awareness and knowledge of maintenance aspects during the design phase. In the case company, the success of design projects in terms of fulfilment of expected properties is only monitored, in the best case, for a single year. There is a potential to follow the performance of the equipment for a longer period to detect maintenance problems and provide feedback to the design process in the format of lessons learned from production. The metrics illustrated in this article could be used as performance metrics for the engineering community. Furthermore, the design guidelines take on the character of procedural guidelines on a macro level and could benefit from moving toward a more analytical micro level of guidelines to support knowledge creation and re-use further. For machinery, maintainability described as a property indirectly influenced by the developer could be treated as a product characteristic as it is one of the main qualities the company wants when buying this kind of product. Design for maintainability could therefore be emphasised in design guidelines. “Smart” maintenance might be an interesting concept to modernise maintenance operations. The main factors in this concept are data-driven decision making, human capital resources, internal and external integration; it is mentioned that all four components are important to become smart. Data could be used in design phase decision-making through deeper integration, not only between production and the acquiring organisation, but also with the suppliers. To be able to do this, human capital and knowledge re-use must be further developed.

5.3. RQ2: What are the barriers that prevent us from capturing, sharing and re-using equipment breakdown knowledge from production into the production equipment acquisition phase?

This study investigates the barriers to how to capturing and transferring maintenance-related knowledge from operations into the process of procuring new equipment. For analysis other than the knowledge transfer barriers from Riege (2005), the activity theory framework for organisational learning is used (Engeström, 2000) as described in Figure 26.

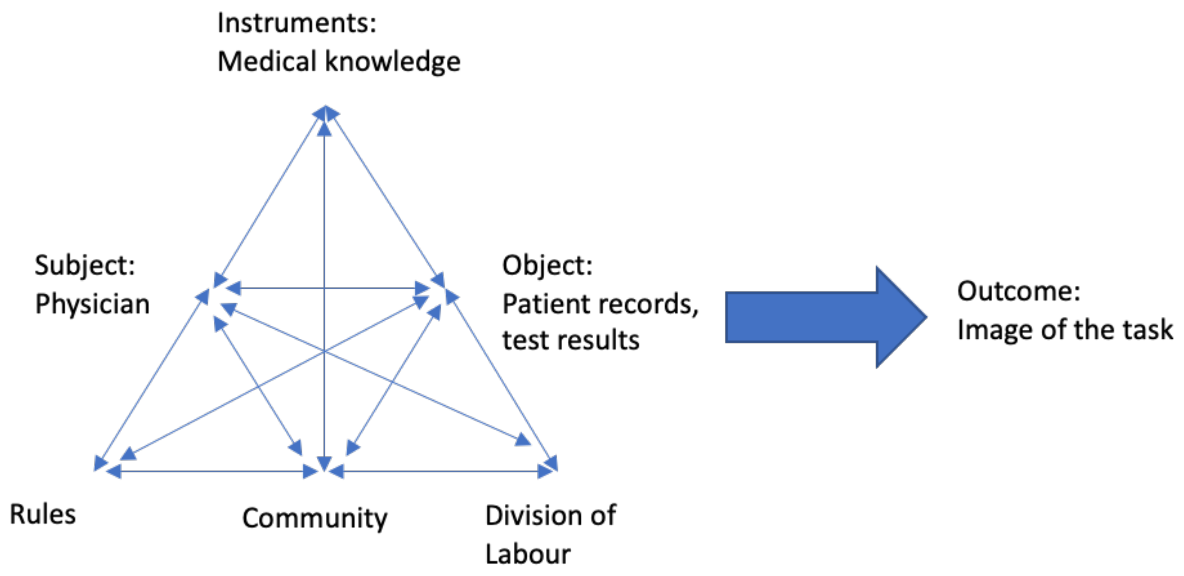


Figure 26: Activity theory for organisational learning, example of hospital application (Engeström, 2000)

For early equipment management, the activity theory model is described as below in Figure 27.

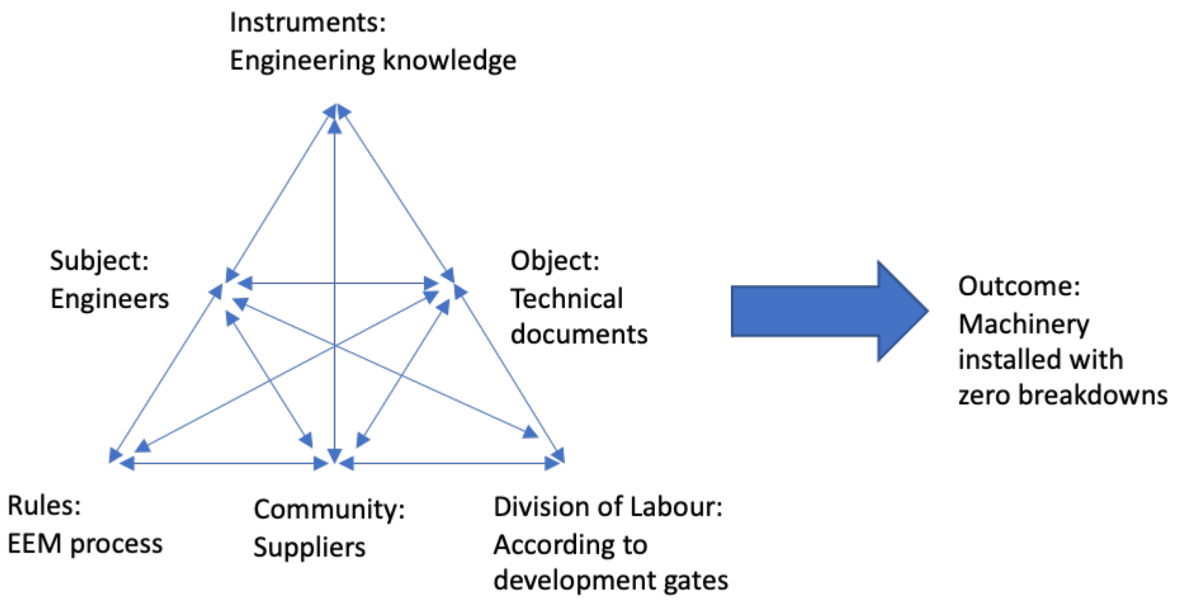


Figure 27: EEM described in activity theory model

From the 30 identified barriers to knowledge re-use by Riege (2005), respondents in the study identified the following 11 barriers as critical (Table 7):

Table 7: Identified knowledge barriers in the study

Individual	Organisational	Technology
Time	Strategy	IT support
Awareness	Directions	
Explicit vs tacit	Support	

Capture	Low priority	
Trust	Infrastructure	

The above barriers are further described below:

Individual:

- A general lack of time to share knowledge
- Low awareness and realisation of the value and benefit of possessed knowledge to others
- Dominance of sharing explicit over tacit knowledge
- Insufficient knowledge capture of past mistakes that would enhance individual and organisational learning effects
- A lack of trust in accuracy and credibility of knowledge

Organisational:

- Missing or unclear integration of knowledge re-use into the company's goals and strategy
- A lack of practices, leadership and managerial direction that clearly communicates the value of knowledge sharing practices
- The existing culture is not providing sufficient support for sharing practices
- Knowledge retention of highly skilled and experienced staff is not a high priority
- Shortage of appropriate infrastructure supporting sharing practices

Technology:

- A lack of IT systems and processes impeded in which way people do things

This shows that the main barriers are in the organisational and the individual dimensions and very few in the technology aspect. The chapters below analyse these barriers from the perspective of the activity theory.

5.3.1. Instruments – Engineering knowledge

According to the barriers to knowledge management (Riege, 2005), mapping the answers of respondents shows clearly that some barriers are more prominent than others and that many suspected barriers were not perceived by the organisation. People did not seem to fear that sharing knowledge might jeopardise someone's job security; competitiveness (neither internal nor external) or organisational hierarchy did seem to be a major problem when it came to sharing knowledge. In addition, age, gender or cultural differences did not seem to influence knowledge flow in a negative way. Technological barriers were also not seen as big obstacles in general.

Barriers mentioned as the biggest hinders to effective knowledge management were described from the perspective that knowledge was not seen as important from both an individual or organisational perspective. For example, there were a few ways of working to collect knowledge, management was not specifically enforcing this activity and there was a lack of infrastructure to either collect, share or re-use knowledge. This is a management issue and needs to be addressed as such while referring back to Riege (2005) on organisational barrier number two: A lack of leadership and managerial direction in terms of clearly communicating the benefits and values of knowledge-sharing practices. Other barriers outside of the framework by Riege (2005) were also identified. For example, the level of competence in totality was increasingly lowered, and even if the processes existed for documenting knowledge not everyone was applying this way of working. A third item highlighted was that knowledge was not always documented in a way that was easy to understand and that there were difficulties in applying the knowledge from another context.

5.3.2. Subjects - Engineers

As mentioned in the theoretical background, maintenance will play an increasing role in the circular economy emerging in society. On that note, from background research, industry often underestimates the cost of maintenance and the importance of not underinvesting in maintenance activities. Maintenance competence will therefore be critical in the future. As seen in Figure 28, the respondents have all been in their corporate roles for a significant period of time. The average number of employment years of respondents was 26 and the educational level was high-school or college. The majority started as operators in production and have acquired a detailed and high-level skill in operational activities. Several respondents related the good working environment and willingness to collaborate that exists in the organisation, especially between company sites.

Figure 28: Average age in the company or in the role of the respondents

5.3.3. Rules - the EEM process

When discussing how respondents worked with the knowledge aspect of EEM, a majority of them stated that EEM is more of a "what and when to do" checklist, similar to a traditional stage gate model, rather than a knowledge management supporting method. On "how do you define EEM", twelve respondents defined it as a structured way of working, a framework and/or a standardised process. Regarding the objective of EEM, the answers were more divergent depending on the role of the individual interviewed but several mentioned classic project objectives, such as being on time and on budget. It was evident that respondents were more focused on the phases and gates rather than on knowledge creation and re-use process to prevent future production disturbances. Referring to theory (Wynn & Clarkson, 2018), this focus reflects a macro-level procedural model rather than a micro-level analytical model which is where theory suggests knowledge management models are most efficient, which is visualised below in Figure 29.

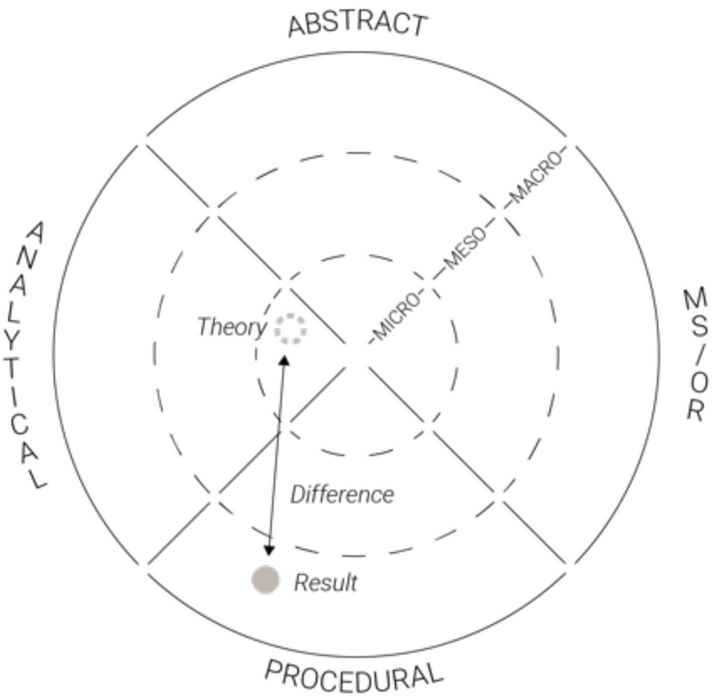


Figure 29: Visualisation of design models and where knowledge management models are found in the theoretical framework vs where the model that the case company is using is located in the framework (Wynn & Clarkson, 2018)

Traditional stage-gate models (macro-level procedural models) emphasise the use of formal, structured reviews to ensure design is sufficiently mature before allowing it to proceed from one stage to the next (Wynn & Clarkson, 2018). A criticism of this traditional approach is that it leads to delayed information and reactive management (Ottosson, 2004). The difficulty of long-term planning in a project involving uncertainty is also highlighted. Micro-level analytical models are on the other hand more suitable for knowledge management (Wynn & Clarkson, 2018). One example is the PROSUS method on knowledge modelling (Blessing, 1994) in which the designer proceeds through iterative cycles intended to capture knowledge regarding proposals, arguments and decisions for each design situation encountered. Other models focus on intelligent history inquiry to help designers understand and re-use past designs, such as the design history system DHS (Shah et al., 1996). This finding suggests that the case company might not use the optimal model to support knowledge management. Further, by looking at the entire EEM system and knowledge value stream, and not only project-by-project, the comparison of how much more knowledge is re-used between each acquisition could be valuable to investigate. Today, measurements used are rather focusing on gates passed on time and vertical ramp-up per project instead of knowledge re-use and how much the entire EEM system has improved.

5.3.4. Community - Suppliers

Many respondents mentioned that the collaboration was excellent, but six interviewees described difficulties in supplier collaboration. These difficulties principally dealt with the structure and the content of the documentation that the case company required from the supplier. A respondant even argued that “I would definitely like to share 3D data on product, process and equipment in both directions and would like for them to work directly with the documentation in our systems”. A Maintenance representative exemplified a conflict when Maintenance needed information and knowledge about a specific component in order to plan their professional maintenance; “I want to be able to repair this, I cannot just scrap it”. The supplier did not want to share his knowledge about the specific component since this related to his own know-how.

Analysing the results, knowledge sharing through documentation between supplier and case company was hindering collaboration. The quality of maintenance work in the project was affected, in this case disturbing their professional maintenance planning thus limiting the possibilities of preventing future production disturbances. Not only did it seem to affect the prevention of future production disturbances, but a purchasing representative even argued that the increasing demand for documentation and maintenance requirements from the case company was making it difficult to find suppliers willing to do business. Studies have indicated that it is critical for any design collaboration initiatives that requirements are set and agreed upon (Axelsson, 2005). Further, the level of supplier responsibility in projects increases as the design is established by the buyer’s requirements (Petersen et al., 2005). This points up the necessity for project success to be detailed and clear on the requirements on both technical aspects but also documentation aspects, even if respondents experienced difficulties with collaboration.

5.3.5. Division of labour – According to development gates

A large majority of the respondents mentioned the macro-procedural model with clear stages and gates as one of the strong parts of the system used. The checklists were specific on which party should perform a certain task and when, but not necessarily given the depth or reasoning on why and how, more the "what" aspect of the task. All sites mentioned time and resources as main challenges. As stated in the theoretical part, this is normally the case for companies that work with a traditional design process. Shifting towards a more lean approach might be valuable, as described in Table 8:

Table 8: Distinction of traditional vs lean product development (Machado, 2006)

	Traditional	**Lean**
Team structure	Teams not used	Cross-functional teams
Development phases	Small overlap	Simultaneous
Integration vs coordination	N/A	Meetings
Project management	Functional team structure	Heavy weight manager
Black box engineering	No	Yes
Supplier involvement	Towards the end of the project	From the beginning of the project

5.3.6. Objects – Technical specification requirements, spare-part lists, maintenance machine ledgers etc.

Twelve respondents mentioned documentation as a concern, both from a content perspective but also as a time-consuming task that required additional resources from both the case company and suppliers. It was also mentioned as an obstacle in collaboration with suppliers.

5.3.7. Outcome – Machine installed with zero losses

It was clear that respondents judged a successful acquisition project depending on their perspective; Maintenance focused on the ease of maintaining the equipment, whereas Purchasing focused on the appropriate cost and Production on equipment capability. A single respondent stated that increased knowledge was an important goal and viewed the benefits from a more holistic perspective.

6. Discussion

In this chapter, the implications of findings on system engineering and engineering design are discussed from several perspectives: managerial aspects regarding capability, the knowledge management aspect, the organisational aspect and, finally, a design model aspect.

6.1. Managerial implications on system engineering and engineering design capability

To be able to improve the design process, it is important to understand effectiveness and efficiency, or the capability of the process Lean has been the way in which to make improvements for several decades and has inspired a variety of disciplines to identify waste and loss. Traditionally, the focus of lean has been on production flows, but the attention is expanding to look further into other processes, such as banking and hospital services, but also into engineering flows (Bhasin, 2015). The term "usable knowledge" is defined as the value-adding part of Lean Product Development. This means that for design of the production system, it is critical to focus on knowledge creation during the design process to enable the production system to support lean principles of production.

Another fundamental lean principle is visualisation. It is important that organisations can understand weaknesses and undertake appropriate improvement actions. The problems in production are easy to detect; it is obvious if the line is standing still or material is piling up. For hidden processes, such as engineering, it is trickier to detect problems. It is vital that hidden processes understand their performance and gain an understanding of their improvement needs. Even if it is more difficult, we should still try. The results from this thesis could be one way of tracking the effectiveness of the engineering process.

There is also a possibility that the production equipment is used in another way than intended from the technical specifications, i.e. the equipment is used differently than it was designed for and might therefore have higher maintenance costs than expected.

6.2. Implications for system engineering and engineering design from a knowledge management perspective

In the analysis part it was identified that the main barriers to effective knowledge management were that knowledge was not viewed so important from either an individual or an organisational perspective. This refers to organisational barrier no. two: "A lack of leadership and managerial direction in terms of clearly communicating the benefits and values of knowledge sharing practices.", a management issue that needs to be addressed as such.

It was mentioned by respondents that the level of competence as a whole is diminished and that even if processes exist for documenting knowledge, not everyone would be applying this way of working. Knowledge is not always documented in an easy way for someone else to understand and there are difficulties to apply the knowledge in another context. A proposal would be to more explicitly share knowledge. Currently, the tacit knowledge possessed by organisations is transferred by study visits, benchmarking and training which are normally organised by corporate teams. Team members viewed these activities as valuable but there was little effort to ensure that knowledge would be shared beyond the immediate team. The proposal would be to ensure that both the emphasis to document already explicit knowledge would be enforced, and that efforts are made to ensure the tacit knowledge would be captured to become explicit knowledge. There are several tools and methods defined as knowledge re-use support, with the aim to assist and realise knowledge flow in an organisation. The study by Stenholm

(2018) regarding engineering check sheets could be very valuable. The intention of these check sheets would not be to manage all existing knowledge and instruct engineers exactly what to do but rather guide them towards making conscious decisions and trade-offs during the design process. The case company had started this, but its actions are more of “what” to do whereas the list should be supplemented with “why” and “how”.

6.3. Implications on system engineering and engineering design from an organisational perspective

As mentioned by Levi (2007), part of creating an effective group is making sure it has the necessary diversity of knowledge and skills. Interdisciplinary research teams are more productive than teams whose members have similar backgrounds. Groups whose members have differences of opinion are more creative than like-minded groups. Management teams whose members have different backgrounds are more innovative than homogenous teams (Guzzo & Dickson, 1996). The advantages of diversity are seen when members are both highly skilled and committed to their goals. The study showed that the group was to a large extent homogenous and that both productivity and creativity could be increased by including more diversw teams in terms of gender, academic background and seniority within the company.

6.4. Implications on system engineering and engineering design from a design model perspective

The study showed that the company is using a more traditional stage-gate model (macro-level procedural model) which emphasises the use of formal, structured reviews to ensure design is sufficiently mature before allowing it to proceed from one stage to the next (Wynn & Clarkson, 2018). Criticism of this traditional approach is that it leads to delayed information and reactive management (Ottosson, 2004). He also highlights the difficulty of long-term planning on project involving uncertainty. Micro-level analytical models on the other hand focus on iterative cycles and are intended to capture knowledge regarding proposals, arguments, and decisions for each design situation encountered. A conclusion is that the company should try to emphasise the iterative way of working in their current model. Further, by looking at the entire EEM *system* and not just project-by-project, a comparison of how much more knowledge is re-used between each acquisition could be valuable. Nowadays, measurements used are rather focusing on gates passed on time and vertical ramp-up per project and not on knowledge re-use and how the entire EEM system is undergoing an improvement process.

7. Contribution to research

In this chapter, the academic contribution to the research gap identified, is presented.

From the research gaps identified, large automotive companies seek answers to the question as to where the main losses are incurred. The methods known are normally only kept within the four walls of the plant. This thesis explores a method to understand the magnitude of losses across an entire value chain.

Secondly, large automotive companies seek answers to understand the effectiveness and efficiency of production system design in the Manufacturing Engineering. This thesis presents data with which to track the performance of engineering during a 25-year period, focusing on equipment breakdown cost as a measurement of engineering performance. The thesis has demonstrated that, in contrast to theory (Deighton, 2016), the maintenance cost per machine increases instead of decreases during the initial phase of the life-cycle. In contrast to ambitions of the design process, new machinery have higher levels of maintenance cost than end-of-life machinery and in contrast to theory, the design weakness share of maintenance stays on a plateau rather than decreasing during the initial phase of the life-cycle. However, this is a small study that requires further research to identify the under-lying factors for the result.

This thesis also shows qualitative lessons learned from four industrial cases where the exact same equipment is re-acquired in a large automotive company, which enables the filtering out of factors and barriers to transferring knowledge during engineering processes.

8. Conclusions

In this chapter, the conclusions from the study are presented for each research question with further potential research identified and described.

Efficient production systems are necessary for the realisation of products that fulfil customer needs and delivery requirements (Bellgran, 2003). Bellgran continues: “Designing a production system is a unique and complex task during which many parameters should be taken into account during the process of creating, evaluating and selecting the proper alternative”. The importance of design, in particular as an industrial activity within the increasingly complex and dynamic context in which it takes place, has led to the desire to improve the effectiveness and efficiency of design practices (Blessing & Chakrabati, 2009). This also applies to the design of production systems. To understand the main problems in a production flow, a pre-study was performed.

Pre-study: What major problems can be identified in an end-to-end production process in a large manufacturing firm?

The study demonstrates that it is relevant to analyse the production disturbance cost from the perspective of multiple plants, and that the result gives indications of major losses for an entire cross-organisational flow for a product equivalent. The study finds that equipment breakdown costs are among the top three factors for the value chain studied, together with waiting time and non-value adding time in the production chain. Equipment breakdown was therefore selected as an area of interest for further investigation and the equipment acquisition process was identified as key to understanding the link between equipment design and equipment performance.

To investigate the effectiveness and efficiency of production system design, this thesis presents comparative case studies from powertrain manufacturing engineering in a large heavy truck company. The focus is on the equipment acquisition process and its impact on the performance of purchased equipment in terms of breakdown cost due to design weakness. The investigation was performed both quantitatively, comparing breakdown costs for newly acquired equipment to equipment nearing the end-of-life, and qualitatively, comparing the ability to prevent breakdowns in four re-purchasing acquisition projects. To improve the production system design process, it is important to understand the effectiveness and efficiency, or capability, of the process.

RQ1: What is the current capability of a manufacturing firm to address equipment breakdown issues already during the production equipment acquisition phase?

By comparing newly designed equipment to equipment approaching their end-of-life, the thesis has concluded that, in contrast to theory, the maintenance cost per machine increases instead of decreases during the initial phase of the life-cycles. In contrast to the ambitions of the design process, new machines have higher level of maintenance cost than end-of-life machines and in contrast to theory, the design weakness share of maintenance problems stays on a plateau rather than decreasing in the initial phase of the life-cycle.

As engineering is a knowledge-intense activity, increasing the capability of the engineering community is one of the most significant factors to focus on to increase knowledge within the engineering community. To make a community of expertise grow in knowledge, it is vital to have a systematic way of capturing, sharing and re-using knowledge and understand the barriers as to why these steps may not take place as effectively as desired.

RQ2: What are the barriers that prevent us from capturing, sharing and re-using equipment breakdown knowledge from production into the production equipment acquisition phase?

From the thirty identified barriers to knowledge re-use, respondents identified eleven barriers as critical. These eleven barriers belong to the individual and organisational rather than the technological dimensions. From an activity theory perspective, other barriers, such as the homogeneity of the engineering community, the strict use of stage gate models, and the misalignment of targets were identified. For further research, the author suggests exploring how to validate the efficiency and effectiveness of production system design, the knowledge management aspects thereof and how the paradigm shift to Industry 4.0 and digitalisation might support the engineering community further.

8.1. Further research

To further explore the improvement potential of the production system design process, there is a need to more deeply understand the complexity of knowledge management. Greater research focus could be placed on understanding if we as a production system design community are getting better at re-using knowledge; perhaps we can continue to use the equipment acquisition process as a laboratory for this purpose. It would also be relevant to learn more about the management regarding individual, global and organisational maintenance knowledge during the production system design process. Firstly, how deep is the knowledge regarding maintenance in production, and secondly, how is that knowledge from production transferred and re-used in designing equipment? As the stage gate model does not necessarily support knowledge management, it would be beneficial to analyse what implications the current way of working with stage gate models has on knowledge management quality and suggest directions ahead.

From the design perspective, with the paradigm shift to digitalisation, it would be relevant to better understand how the production system design process might benefit from digitalisation. An example is how documentation, such as technical specifications shared between partners, could be performed in a secure but efficient manner. On that topic, it would also be valuable to investigate any potential resistance to digitalisation among engineers and any socio-technological barriers to using digital tools.

Connected to the design perspective, it would be valuable to obtain more qualitative data reflecting on the quantitative data that is presented in this paper; how does the organisation interpret the data and are there other parameters that were not considered by just looking at quantitative data? Comparing data from the case company to other industries would be highly relevant to understanding the validity of conclusions outside of the case studied. The discussion note that the purchased equipment might not be used according to the technical specifications would be relevant for better understanding; consequently, the field of validating the connection between actual usage and design of the equipment is a topic of interest going forward.

A literature review on the impact of Industry 4.0 on product design and development (Pereira Pessôa & Jauregui Becker, 2020) mentions that there will be a need for new product design processes that integrate design models that are not document driven, but rather model driven. With model driven system engineering, visual modelling principles and best-practices could be used through-out the life-cycle of the product to facilitate an understanding and simplify communication in a multi-disciplinary development team. A recommendation for further research would be to investigate the use of documentation in product system design projects and evaluate their effectiveness by comparing the quality of the documentation to high- and low performing equipment. Some examples of these documents that might be worthy of further study are acceptance records, handover records, meeting minutes, technical specifications, scope of supply and white books. Based on the findings, the expected dependencies between production and design could be further developed.

REFERENCES:

Alves, J. R. X., & Alves, J. M. (2015, 2015/09/02). Production management model integrating the principles of lean manufacturing and sustainability supported by the cultural transformation of a company. *International Journal of Production Research, 53*(17), 5320-5333. https://doi.org/10.1080/00207543.2015.1033032

Ardichvili, A., Page, V., & Wentling, T. (2003). Motivation and barriers to participation in virtual knowledge‐sharing communities of practice. *Journal of Knowledge Management, 7*(1), 64-77. https://doi.org/10.1108/13673270310463626

Axelsson, E. A. (2005). *Effektivare tillverkning! Handbok för att systematiskt arbeta bort produktionsstörningar*. Swedish Institute for Standards. Stockholm, Sweden

Bellgran, M. (2003). Design wisdom of production system designers. Proceedings of the 5th European Academy of Design Conference, Barcelona, Spain

Bellgran, M., & Säfsten, K. (2005). *Produktionsutveckling*. Studentlitteratur. Lund, Sweden

Bellgran, M., & Säfsten, K. (2009). *Production development: Design and Operation of Production Systems*. Springer.

Bhasin, S. (2015). *Lean Management Beyond Manufacturing: A Holisitc Approach*. Springer. Cham, Switzerland

Blanchard, B., & Fabrycky, W. (1998). *Systems Engineering and Analysis* (3 ed.). Prentice Hall. Englewood Cliffs, US

Blessing, L. (1994). *A process-based approach to computer-supported engineering design* University of Twente]. Enschede, Netherlands.

Blessing, L., & Chakrabati, A. (2009). *DRM, a Design Research Methodology* (1 ed.). Springer. London. UK

Bokrantz, J., Skoogh, A., Berlin, C., & Stahre, J. (2017, 2017/09/01/). Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030. *International Journal of Production Economics, 191*, 154-169. https://doi.org/https://doi.org/10.1016/j.ijpe.2017.06.010

Bouwmans, P. (2003). *Purchasing knowledge: Key to purchasing performance* Eindhoven University of Technology]. Eindhoven, Netherlands.

Bruch, J. (2012). *Management of Design Information in the Production System Design Process* [PhD dissertation, Mälardalen University].

Chinowsky, P., & Carrillo, P. (2007). Knowledge Management to Learning Organization Connection. *Journal of Management in Engineering, 23*(3), 122-130. https://doi.org/doi:10.1061/(ASCE)0742-597X(2007)23:3(122)

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative and mixed* *methods approaches*. SAGE Publications, Inc.

Creswell, J. W., & Plano Clar, V. L. (2017). *Designing and Conducting Mixed Methods Research*. SAGE Publications, Inc.

Cross, N. (1984). *Developments in design methodology*. John Wiley & Sons, Inc. Chichester, New York, US

Davenport, T. H., & Prusak, L. (1998). *Working Knowledge: How Organizations Manage What They Know*. Harvard Business School.

Deighton, M. (2016). *Facilities Integrity Management: Effective Principles and Practices for the Oil, Gas and Petrochemical Industries*. Gulf Professional Publishing.

Denger, A., & Zamazal, K. (2020). Product lifecycle challenges for powertrain systems in the automotive industry. *Systems Engineering for Automotive Powertrain Development*, 1-18. Springer. Cham, Switzerland

Dretske, F. (1981). *Knowledge and the flow of information*. MIT press.

Dülgerler, M., & Negri, M. (2016). Lessons (Really) Learned? How to Retain Project Knowledge and Avoid Recurring Nightmares: Knowledge Management and Lessons Learned. Paper presented at PMI® Global Congress 2016 - EMEA, Barcelona, Spain. Newton Square, PA: Project Management Institute.

Eckert, C. M., Clarkson, P. J., & Stacey, M. K. (2003). The spiral of applied research - a methodological view on integrated design research. ICeD03: 14th international conference on engineering design, Stockholm, Sweden.

effectiveness. (2021). *Merriam-Webster.com*. https://www.merriam-webster.com/dictionary/effectiveness

efficiency. (2021). *Merriam-Webster.com*. https://www.merriam-webster.com/dictionary/efficiency

Engeström, Y. (2000). Activity theory as a framework for analysing and redesigning work. *Ergonomics, 43*(7), 960-974.

Folkestad, J. E., & Johnson, R. L. (2001). Resolving the conflict between design and manufacturing: Integrated Rapid Prototyping and Rapid Tooling (IRPRT). *Journal of Industrial Technology, 17*(4).

Grieves, M. (2006). *Product Lifecycle Management*. McGraw-Hill.

Gulati, R. (2013). *Maintenance and Reliability Best Practices* (2 ed.). Industrial Press.

Guzzo, R., & Dickson, M. (1996). Teams in organizations: recent research on performance and effectiveness. *Annual review of psychology, 47*, 307-338.

Hoegl, M., & Wagner, S. M. (2005). Buyer-Supplier Collaboration in Product Development

Projects. *Journal of Management, 31*(4), 530-548. https://doi.org/10.1177/0149206304272291

Hubka, V., & Eder, W. E. (1988). *Theory of technical systems*. Springer. Berlin, Germany

Insight, F. B. (2021). *Industry 4.0 market size, share and COVID-19 impact analysis, by application (...), by vertical (...) and Regional forecast 2021-2028*. F. B. Insight.

Isaksson, O., Eckert, C., Panarotto, M., & Malmqvist, J. (2020). YOU NEED TO FOCUS TO VALIDATE. *Proceedings of the Design Society: DESIGN Conference, 1*, 31-40. https://doi.org/10.1017/dsd.2020.116

Islam, M. H., Chavez, Z., Birkie, S. E., & Bellgran, M. (2020, 2020//). Key Factors on Utilizing the Production System Design Phase for Increasing Operational Performance. Advances in Production Management Systems. Towards Smart and Digital Manufacturing, Cham.

Jha, K. N., & Iyer, K. C. (2007, 2007/07/01/). Commitment, coordination, competence and the iron triangle. *International Journal of Project Management, 25*(5), 527-540. https://doi.org/https://doi.org/10.1016/j.ijproman.2006.11.009

Johnson, R. B., & Onwuegbuzie, A. J. (2007). *Towards a definition of mixed methods research*. SAGE Publications.

Jonsson, P., & Mattsson, S. A. (2009). *Manufacturing, planning and control*. McGraw-Hill education.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014, 2014/08/01). Industry 4.0. *Business & Information Systems Engineering, 6*(4), 239-242. https://doi.org/10.1007/s12599-014-0334-4

Le Dain, M.-A., Blanco, E., & Summers, J. (2013, 08/19). Assessing Design Research Quality: Investigating Verification and Validation Criteria. *Proceedings of the International Conference on Engineering Design, ICED, 2*.

Lee, C., & Yang, J. (2000). Knowledge value chain. *Journal of Management Development, 19*(9), 783-794. https://doi.org/10.1108/02621710010378228

Lee, M.-C. (2016, 01/01). Knowledge management and innovation management: Best practices in knowledge sharing and knowledge value chain. *International Journal of Innovation and Learning, 19*(2), 206-226. https://doi.org/10.1504/IJIL.2016.074475

Levi, D. (2007). *Group dynamics for teams*. SAGE Publications.

Li, D., Fast-Berglund, Å., & Paulin, D. (2019, 2019/12/01). Current and future Industry 4.0 capabilities for information and knowledge sharing. *The International Journal of Advanced Manufacturing Technology, 105*(9), 3951-3963. https://doi.org/10.1007/s00170-019-03942-5

Lundgren, C. (2019). *Smart Maintenance Investments - ways to quantify effects and factors influencing the investment process* Chalmers University of Technology].

Löfgren, K. G. (1983). *Produktion - teknik och ekonomi*. Liber-Hermods. Malmö, Sweden

Machado, M. (2006, 11/01). CRIAÇÃO DE VALOR NO PROCESSO DE DESENVOLVIMENTO DE PRODUTOS: UMA AVALIAÇÃO DA APLICABILIDADE DOS PRINCÍPIOS E PRÁTICAS ENXUTAS. *Revista Gestão Industrial, 2*. https://doi.org/10.3895/S1808-04482006000300010

McNichols, D. (2010). Optimal knowledge transfer methods: a Generation X perspective. *Journal of Knowledge Management, 14*(1), 24-37. https://doi.org/10.1108/13673271011015543

Milton, N. (2010). *Lessons Learned Approaches. The Lessons Learned Handbook: Practical Approaches to Learning from Experience* (1 ed.). Chandos Publishing.

Morgan, J. M., & Liker, J. K. (2006). *The Toyota Product Development System: Integrating People, Process, and Technology* (1 ed.). Productivity Press.

Nonaka, I., & Takeuchi, H. (1995). *The Knowledge-Creating Company, How japanese companies create the dynamics of innovation*. Oxford University Press Inc.

OECD. (2005). *Oslo Manual*. https://doi.org/doi:https://doi.org/10.1787/9789264013100-en

Ottosson, S. (2004, 2004/03/01/). Dynamic product development — DPD. *Technovation, 24*(3), 207-217. https://doi.org/https://doi.org/10.1016/S0166-4972(02)00077-9

P&S Intelligence. (2018). *Global Electric Truck Market, by vehicle type (2013-2025)*.

Pahl, G., & Beitz, W. (1996). *Engineering Design - a systematic approach* Springer. London, UK

Penny, R. K. (1970). Principles of engineering design. *Postgraduate Medical Journal, 46*(536), 344-349. https://doi.org/10.1136/pgmj.46.536.344

Pereira Pessôa, M. V., & Jauregui Becker, J. M. (2020, 2020/04/01). Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development. *Research in Engineering Design, 31*(2), 175-195. https://doi.org/10.1007/s00163-020-00330-z

Petersen, K. J., Handfield, R. B., & Ragatz, G. L. (2005, 2005/04/01/). Supplier integration into new product development: coordinating product, process and supply chain design. *Journal of Operations Management, 23*(3), 371-388. https://doi.org/https://doi.org/10.1016/j.jom.2004.07.009

Pistikopoulos, E. N., Vassiliadis, C. G., & Papageorgiou, L. G. (2000, 2000/07/15/). Process design for maintainability: an optimization approach. *Computers & Chemical Engineering, 24*(2), 203-208. https://doi.org/https://doi.org/10.1016/S0098-1354(00)00514-7

Porter, M. E. (1985). *Competitive advantage: Creating and sustaining competitive advantage*.

Free Press. New York, US

Powell, T. (2001). The Knowledge Value Chain (KVC): How to Fix It When It Breaks. KnowledgeNets 2001, New York

Project Management Institute. (2017). *Guide to the Project Management Body of Knowledge (PMBOK® Guide)* (6 ed.). Project Management Institute, Inc.

Riege, A. (2005). Three-dozen knowledge-sharing barriers managers must consider. *J. Knowl. Manag., 9*, 18-35.

Salonen, A. (2018, 2018/01/01/). The need for a holistic view on dependable production systems. *Procedia Manufacturing, 25*, 17-22. https://doi.org/https://doi.org/10.1016/j.promfg.2018.06.052

Salonen, A., & Tabikh, M. (2016, 2016//). Downtime Costing—Attitudes in Swedish Manufacturing Industry. Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015), Cham.

Schacht, S., & Maedche, A. (2016). *A Methodology for Systematic Project Knowledge Reuse*. Springer. Berlin, Germany

Schwab, K. (2017). *The fourth industrial revolution*. Currency. New York, US

Senge, P. (1990). *The art and practice of the learning organization*. Doubleday. New York, US

Shah, J. J., Jeon, D. K., Urban, S. D., Bliznakov, P., & Rogers, M. (1996, 1996/05/01/). Database infrastructure for supporting engineering design histories. *Computer-Aided Design, 28*(5), 347-360. https://doi.org/https://doi.org/10.1016/0010-4485(95)00054-2

Sherwin, D. (2000). A review of overall models for maintenance management. *Journal of Quality in Maintenance Engineering, 6*, 138-164.

SIS. (2000). *SS 441 0505* Swedish Institute for Standards.

Stark, R., Kind, S., & Neumeyer, S. (2017). Innovations in digital modelling for next generation manufacturing system design. *Cirp Annals-manufacturing Technology, 66*, 169-172.

Stenholm, D. (2018). *Reuse of Engineering Knowledge: Support for effective reuse of experience-based codified knowledge in incremental product development.* Chalmers University of Technology]. Gothenburg, Sweden.

Stenholm, D., Catic, A., & Bergsjö, D. (2019). Knowledge reuse in industrial practice: evaluation from implementing engineering checksheets in industry. *Design Science, 5*, Article e15. https://doi.org/10.1017/dsj.2019.10

Tortorella, G. L., Marodin, G. A., Fettermann, D. d. C., & Fogliatto, F. S. (2016, 2016/05/18). Relationships between lean product development enablers and problems. *International Journal of Production Research, 54*(10), 2837-2855. https://doi.org/10.1080/00207543.2015.1106020

Ullman, D. G. (2003). *The mechanical design process*. McGraw-Hill.

Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2020). *Product Design and Development*. McGraw-Hill Education.

Vance, D. (1997). Information, knowledge and wisdom: The epistemic hierarchy and computer-based information systems AMCIS 1997 Proceedings,

Wakiru, J., Pintelon, L., Muchiri, P. N., & Chemweno, P. (2018, 2018/01/01/). Maintenance Optimization: Application of Remanufacturing and Repair Strategies. *Procedia CIRP, 69*, 899-904. https://doi.org/https://doi.org/10.1016/j.procir.2017.11.008

Walden, D. D. (2012, 2012). No Longer Condemned to Repeat: Turning Lessons Learned into Lessons Remembered. Complex Systems Design & Management, Berlin, Heidelberg.

Ward, A. (2007). *Lean product and process development*. Lean Institute.

Weber, R. O., Aha, D., & Becerra-Fernandez, I. (2001). Intelligent lessons learned systems. *Expert Syst. Appl., 20*, 17-34.

Weyer, S., Schmitt, M., Ohmer, M., & Gorecky, D. (2015, 2015/01/01/). Towards Industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems. *IFAC-PapersOnLine, 48*(3), 579-584. https://doi.org/https://doi.org/10.1016/j.ifacol.2015.06.143

Wilkesmann, M., & Wilkesmann, U. (2011, 05/17). Knowledge transfer as interaction between experts and novices supported by technology. *VINE, 41*, 96-112. https://doi.org/10.1108/03055721111134763

Womack, J. J., Jones, D. T., & Roos, D. (1990). *The machine that changed the world*. MacMillan International.

Wu, B. (1994). *Manufacturing systems design and analysis* (2 ed.). Chapman and Hall.

Wynn, D. C., & Clarkson, P. J. (2018, 2018/04/01). Process models in design and development. *Research in Engineering Design, 29*(2), 161-202. https://doi.org/10.1007/s00163-017-0262-7

Yeo, K. T., & Ning, J. H. (2006, 2006/05/16/). Managing uncertainty in major equipment procurement in engineering projects. *European Journal of Operational Research, 171*(1), 123-134. https://doi.org/https://doi.org/10.1016/j.ejor.2004.06.036